전자물리특강:
OLED Light Emission and Outcoupling

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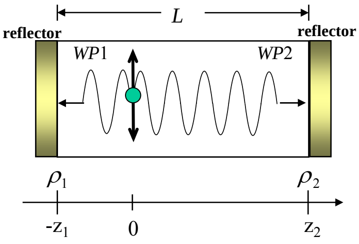
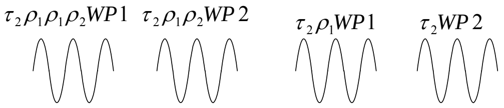
Spontaneous emission from planar microcavity





Where, L : cavity length

ρ_1, ρ_2 : reflection coefficient

τ_1, τ_2 : transmission coefficient

$WP1$, $WP2$: wave packet

$$E_{L2}(t) = \tau_2 WP(t) + \tau_2\rho_1 WP(t - \frac{2z_1}{c}) + \tau_2\rho_1\rho_2 WP(t - \frac{2L}{c})$$
$$+ \tau_2\rho_1\rho_1\rho_2 WP(t - \frac{2z_1}{c} - \frac{2L}{c})$$

D. G. Deppe, C. Lei, C. C. Lin, and D. L. Huffaker, J. Modern Optics **41**, 325 (1994)

Spontaneous emission from planar microcavity

$$E_{L2}(\omega)=\frac{\tau_2}{2\pi}\overbrace{\int_{-\infty}^{\infty}WP(t)\exp(i\omega t)dt}^{WP(\omega)}+\frac{\tau_2\rho_1}{2\pi}\int_{-\infty}^{\infty}WP(t-\frac{2z_1}{c})\exp(i\omega t)dt$$

$$+\frac{\tau_2\rho_1\rho_2}{2\pi}\int_{-\infty}^{\infty}WP(t-\frac{2L}{c})\exp(i\omega t)dt$$

$$+\frac{\tau_2\rho_1\rho_1\rho_2}{2\pi}\int_{-\infty}^{\infty}WP(t-\frac{2z_1}{c}-\frac{2L}{c})\exp(i\omega t)dt+....$$

$$E_{L2}(\omega)=\tau_2WP(\omega)+\tau_2\rho_1e^{i\frac{2\omega z_1}{c}}WP(\omega)+\tau_2\rho_1\rho_2e^{i\frac{2\omega L}{c}}WP(\omega)$$

$$+\tau_2\rho_1\rho_2\rho_1e^{i\frac{2\omega z_1}{c}+i\frac{2\omega L}{c}}WP(\omega)+\tau_2\rho_1\rho_2\rho_1\rho_2e^{i\frac{4\omega L}{c}}WP(\omega)+......$$

$$=\tau_2WP(\omega)[1+\rho_1e^{i\frac{2\omega z_1}{c}}+\rho_1\rho_2\rho_1e^{i\frac{2\omega z_1}{c}+i\frac{2\omega L}{c}}+...$$

$$+\rho_1\rho_2e^{i\frac{2\omega L}{c}}+\rho_1\rho_2\rho_1\rho_2e^{i\frac{4\omega L}{c}}+...\ ]$$

Spontaneous emission from planar microcavity

$$E_{L2}(\omega)=\tau_2WP(\omega)[1+\rho_1e^{i\frac{2\omega z_1}{c}}\{1+\rho_2\rho_1e^{i\frac{2\omega L}{c}}+...\}$$

$$+\rho_1\rho_2e^{i\frac{2\omega L}{c}}\{1+\rho_1\rho_2e^{i\frac{2\omega L}{c}}+...\}]$$

$$1+\rho_2\rho_1e^{i\frac{2\omega L}{c}}+...=\frac{1}{1-\rho_2\rho_1e^{i\frac{2\omega L}{c}}}$$

$$\boxed{E_{L2}(\omega)=\tau_2WP(\omega)\frac{1+\rho_1e^{i\frac{2\omega z_1}{c}}}{1-\rho_1\rho_2e^{i\frac{2\omega L}{c}}}}$$

Spontaneous emission from planar microcavity

$$|\rho_1|^2 = R_1 \;, |\rho_2|^2 = R_2 \;, |\tau_2|^2 = 1 - R_2$$

Emission spectrum in the forward direction

Interference effect

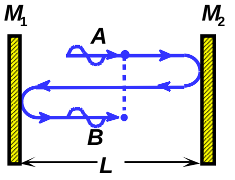
$$|E_{L2}(\omega)|^2 = \frac{(1-R_2)[1+R_1+2\sqrt{R_1}\cos(\frac{2\omega n z_1}{c})]}{1+R_1R_2-2\sqrt{R_1R_2}\cos(\frac{2\omega L}{c})}|WP(\omega)|^2$$

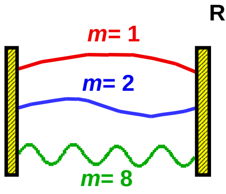
Fabry-Perot Resonator

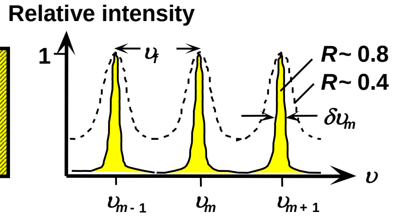
$$= \frac{(1-R_2)[1+R_1+2\sqrt{R_1}\cos(\frac{4\pi n z_1}{\lambda})]}{1+R_1R_2-2\sqrt{R_1R_2}\cos(\frac{4\pi n L}{\lambda})}|WP(\omega)|^2$$

D. G. Deppe, C. Lei, C. C. Lin, and D. L. Huffaker, J. Modern Optics **41**, 325 (1994)

Fabry-Perot optical cavity

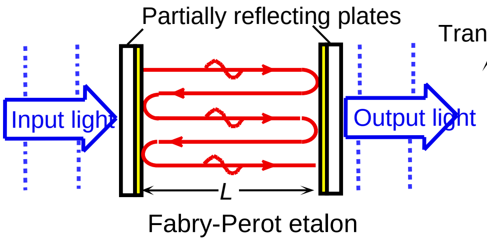




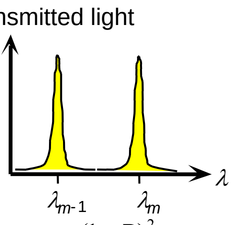


$$E_{cavity} = \frac{A}{1 - r^2 e^{-j2nkL}} \qquad I_{cavity} = \frac{I_o}{(1-R)^2 + 4R\sin^2(nkL)} \qquad \text{finesse (F) of the cavity}: F = \frac{\nu_f}{\delta\nu_m} = \pi\frac{\sqrt{R}}{1-R}$$

The maximum intensity occurs whenever $nkL = m\pi$. These maxima correspond to the allowed cavity modes.



Fabry-Perot etalon



$$\frac{I_{transmitted}}{I_{incident}} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(nkL)}$$

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Spontaneous emission from planar microcavity

If there is phase shift ϕ_m for the reflection at the metal electrode,

$$I_{ext}(z,\lambda) = \frac{(1-R_2)[1+R_1+2\sqrt{R_1}\cos(\frac{4\pi nz}{\lambda}+\phi_m)]}{1+R_1R_2-2\sqrt{R_1R_2}\cos(\frac{4\pi nL}{\lambda}+\phi_m)} I_{\text{int}}(\lambda)$$

Resonance occurs when the denominator is a minimum, i.e., cosine term =1.

$$\boxed{L = \frac{N\lambda}{2n} + \left|\frac{\phi_m}{4\pi n}\right|\lambda, \ (N = \text{integer}, n = \text{refractive index})}$$

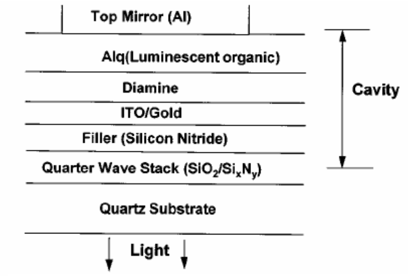
Resonance occurs when the emitting layer is at λ/4 from the reflective electrode.

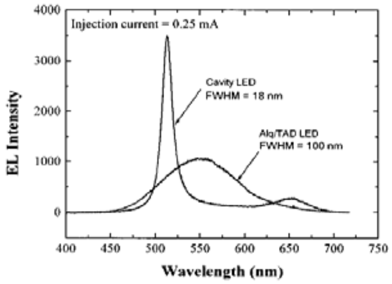
$$\boxed{G_e = \frac{\zeta}{2}\frac{(1-R_2)(1+\sqrt{R_1})^2}{(1-\sqrt{R_1R_2})^2}\frac{\tau_{cav}}{\tau}}$$

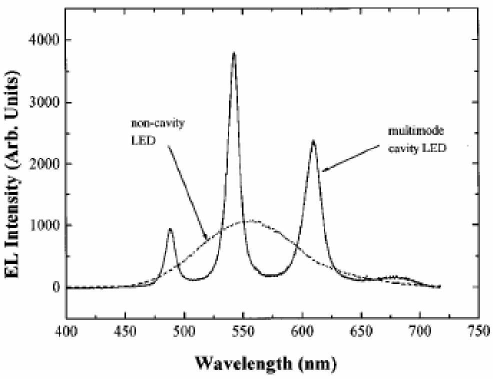
Gain factor for emission from cavity.
G_e=4.1 for Alq3 doped with pyromethene 580.

A. Dodabalapur, L. J. Rothberg, R. H. Jordan, T. M. Miller, R. E. Slusher, and J. M. Phillips, J. Appl. Phys. 80, 6954 (1996).

Resonant emission from microcavity







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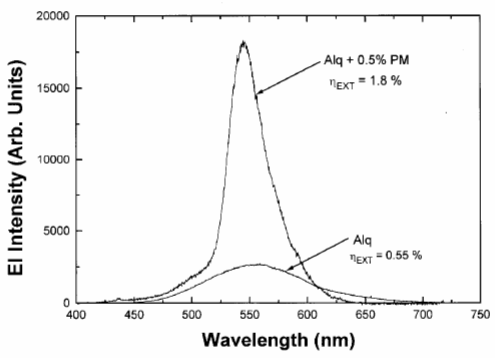
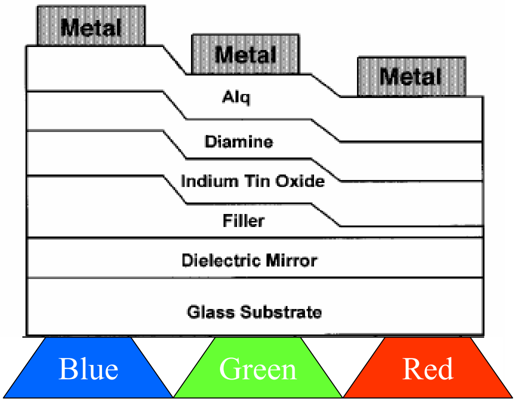


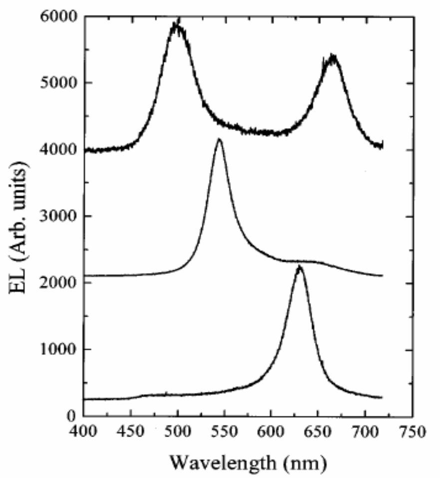
TABLE I. Angular and integrated enhancements of cavity devices with Alq+0.5% PM emissive layers relative to noncavity devices with the same emissive material. The maximum θ is the angle with respect to the cavity axis at which the maximum angular intensity is attained.

Cavity resonance (nm)	Integrated enhancement	Angular enhancement (max θ)
545	0.85	$3.3(0^0)$
560	1.76	$3.7(10^0)$
580	1.62	$1.6(40^0)$
630	0.31	$1.2(60^0)$

A. Dodabalapur, L. J. Rothberg, R. H. Jordan, T. M. Miller, R. E. Slusher, and J. M. Phillips, J. Appl. Phys. **80**, 6954 (1996).

Resonant emission from microcavity





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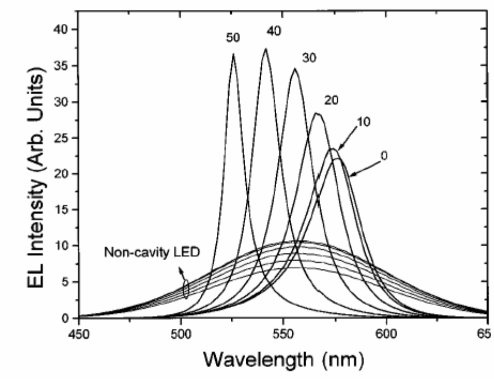
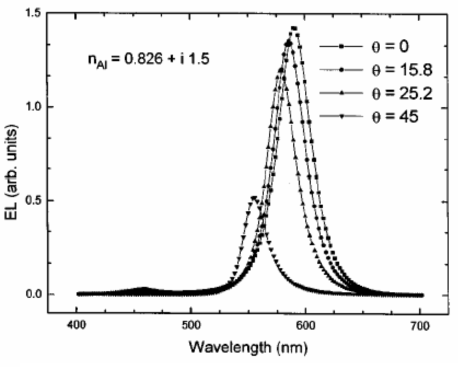
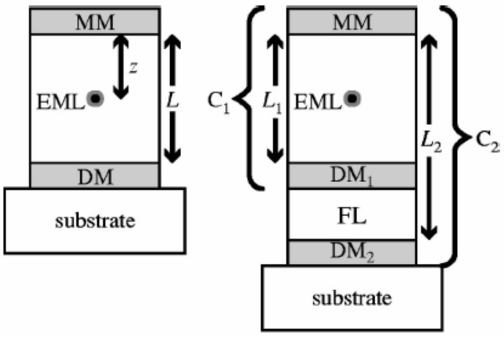
Resonant emission from microcavity





A. Dodabalapur, L. J. Rothberg, R. H. Jordan, T. M. Miller, R. E. Slusher, and J. M. Phillips, J. Appl. Phys. **80**, 6954 (1996).

Multiwavelength resonant cavities for white OLEDs



$$L = \frac{2\pi N - \phi_{MM} - \phi_{DM}}{4\pi n}\lambda$$

$(N = \text{integer}, n = \text{refractive index})$

$$\theta_{MM} \approx \theta_{DM} \approx \pi \qquad L_i = \frac{N_i \lambda_i}{2}(i = 1,2)$$

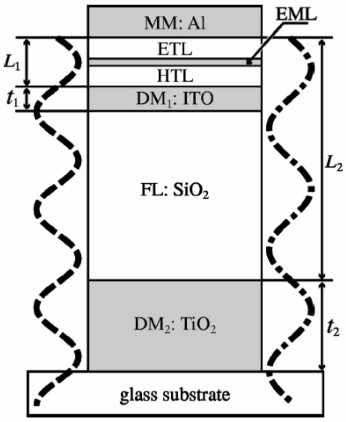


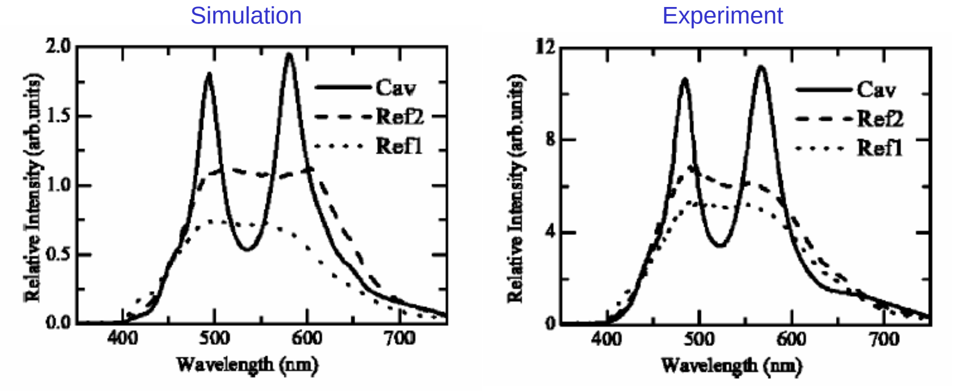
FIG. 2. The structure of the multiwavelength resonant cavity OLED. The dashed line on the left side and the dash-dotted line on the right side show the standing wave of the blue light ($\lambda_1 = 470$ nm) and orange one ($\lambda_2 = 580$ nm), respectively. Here, $L_1 = \lambda_1/2$, $t_1 = \lambda_1/4$, $L_2 = 2\lambda_2$, and $t_2 = 3\lambda_2/4$. The vertical scale is in optical length. LiF and CuPc layers are omitted.

T. Shiga, H. Fujikawa, and Y. Taga, J. Appl. Phys. 93, 19 (2003).

Multiwavelength resonant cavities for white OLEDs

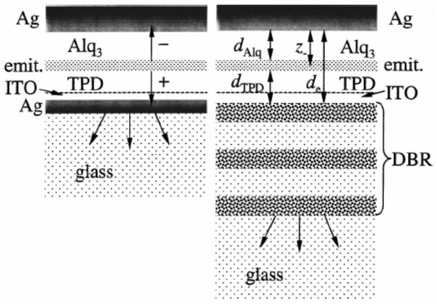
Simulation

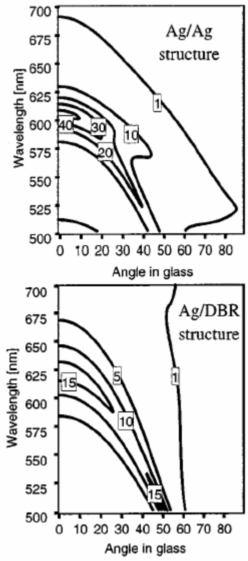
Experiment

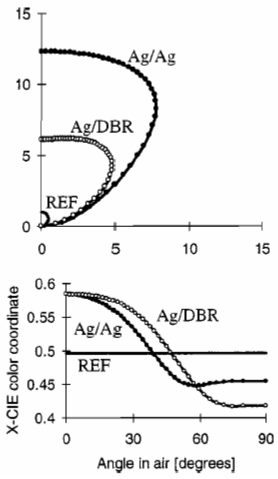


T. Shiga, H. Fujikawa, and Y. Taga, J. Appl. Phys. 93, 19 (2003).

Semitransparent metal or distributed Bragg reflector for wide-viewing-angle OLED microcavities

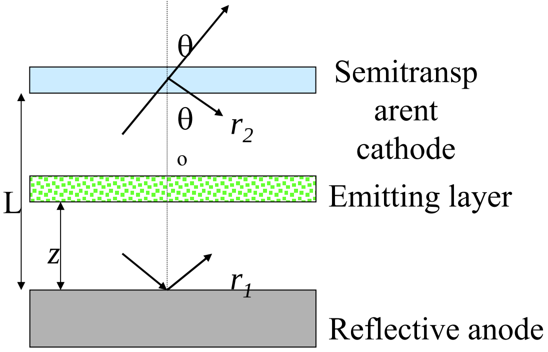






C. Neyts, P. D. Visschere, D. K. Fork,and G. B. Anderson, J. Opt. Soc. Am. B **17**, 114 (2000).

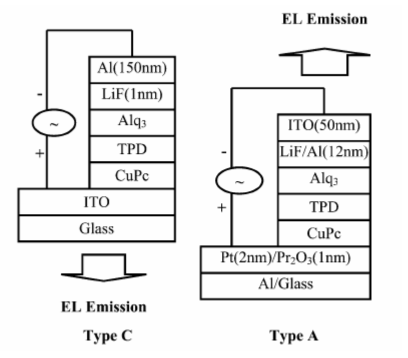
Radiation mode in top-emitting OLED

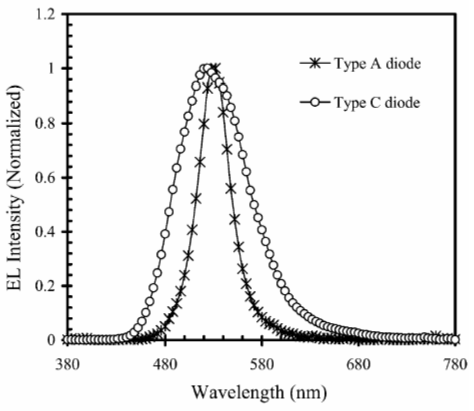


$$I_{ext}^{(s,p)}(\theta,\lambda)=\frac{\left|1+r_1^{(s,p)}\exp(i\frac{4\pi nz\cos\theta_o}{\lambda})\right|^2}{\left|1-r_1^{(s,p)}r_2^{(s,p)}\exp(i\frac{4\pi nL\cos\theta_o}{\lambda})\right|^2}T_2^{(s,p)}I_{\text{int}}^{(s,p)}(\lambda)$$

C. Qiu, H. Peng, H. Chen, Z. Xie, M. Wong, and H. S. Kwok, IEEE Trans. on Electron Dev. 51, 1207 (2004).

Radiation mode in top-emitting OLED





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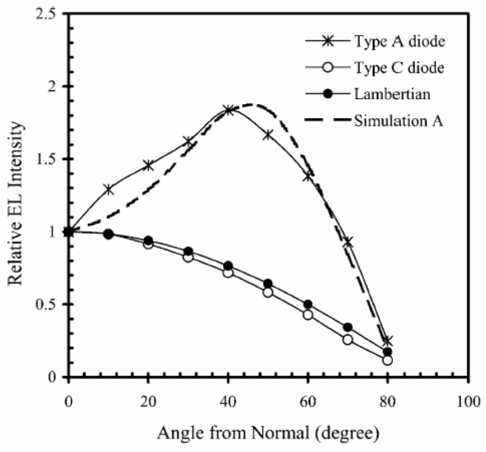
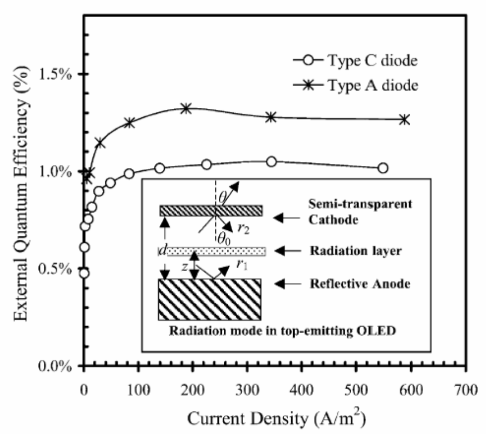


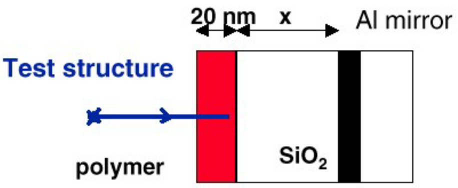


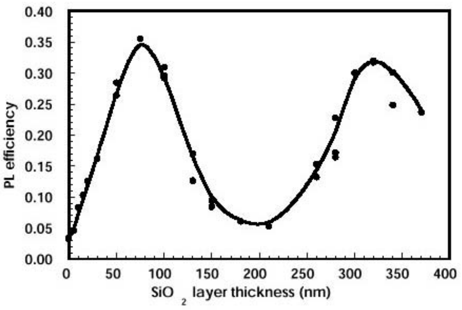
C. Qiu, H. Peng, H. Chen, Z. Xie, M. Wong, and H. S. Kwok, IEEE Trans. on Electron Dev. 51, 1207 (2004).

EL efficiency *vs* distance from a cathode

Optical interference

- Radiation from dipoles depends on local environment
- Interference between reflections modifies
- • Spectrum
- • angular distribution
- • radiative recombination rate
- • efficiency





H. Becker, S. E. Burns, and R. H. Friend, Phys. Rev. B **56**, 1893(1997).

PL efficiency vs x

Efficiency of OLEDs

$$\eta_{ext} = \frac{L_{total}}{JV},$$

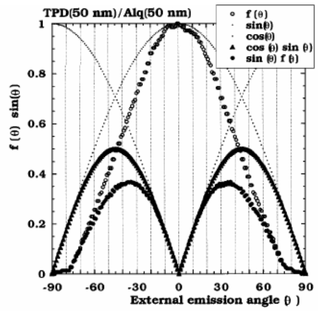
$$L_{total} = \int_0^{\frac{\pi}{2}} 2\pi L(\theta)\sin\theta d\theta,$$

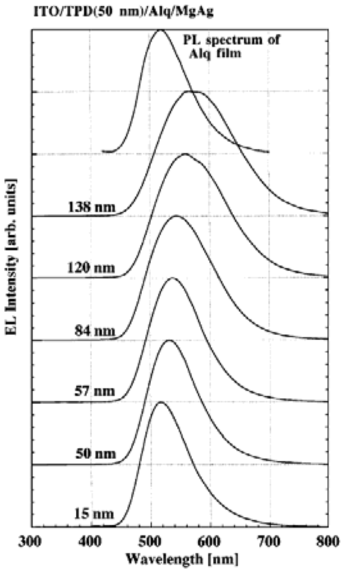
$$L(\theta) = L_o f(\theta)$$

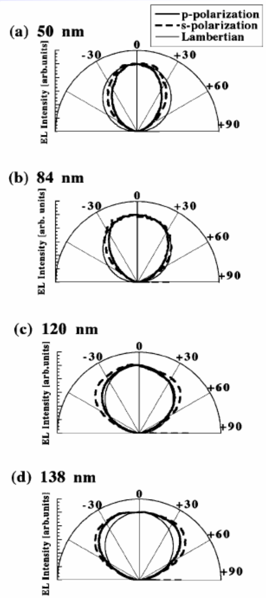
For a Lambertian source,

$$f(\theta) = \cos\theta.$$

$$\therefore L_{total} = \pi L_o$$







Takashi Yamasaki, Kazuhiro Sumioka, and Tetsuo Tsutsui, Jpn. J. Appl. Phys. **38**, 2799 (1999).

External Quantum Efficiency

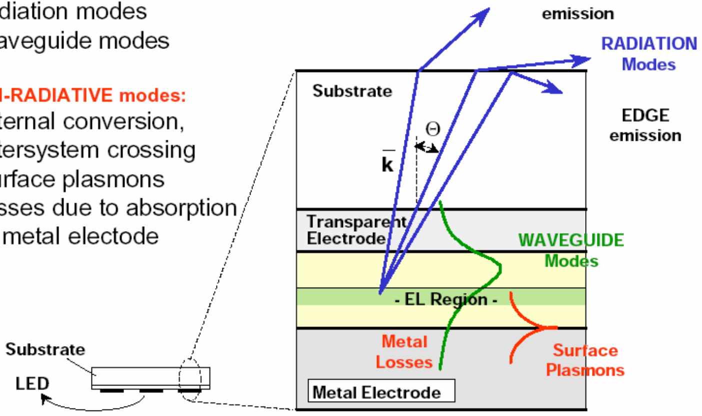
$$\text{Couple-out efficiency: } \chi_{EL} = 1-(1-\frac{1}{n^2})^{1/2} \approx \frac{1}{2n^2} \approx 20\,\% \text{ for } n = \sqrt{\varepsilon} \approx 1.7$$

RADIATIVE modes:

* radiation modes
* waveguide modes

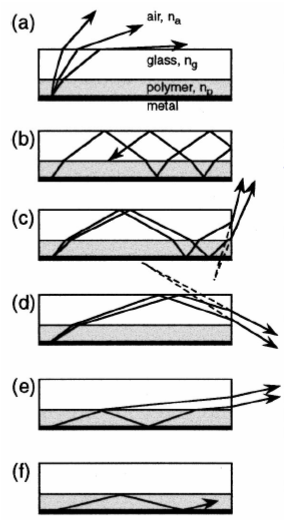
NON-RADIATIVE modes:

* internal conversion, intersystem crossing
* surface plasmons
* losses due to absorption in metal electode



Ref. M.-H. Lu, and J. C. Sturm, J. Appl. Phys. 91, 595 (2002)

Surface vs edge emission

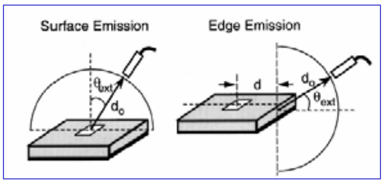


surface-escape $$0 \le \theta < \theta_1,\ \theta_1 = \sin^{-1}\left(\frac{n_a}{n_p}\right) = 30^o \text{ if } n_a = 1, n_p = 2$$

no-escape
absorbed by the metal
$$\theta_1 \le \theta < \theta_2,\ \theta_2 = 36.3^o \text{ if } n_a = 1, n_g = 1.55, n_p = 2.$$
$$\theta_2 = \sin^{-1}\left\{\frac{n_g}{n_p}\sin\left[\cos^{-1}\left(\frac{n_a}{n_g}\right)\right]\right\} = \sin^{-1}\left\{\frac{n_g}{n_p}\cos\left[\sin^{-1}\left(\frac{n_a}{n_g}\right)\right]\right\}$$

m=2
m=1
m=0
leaky
waveguide

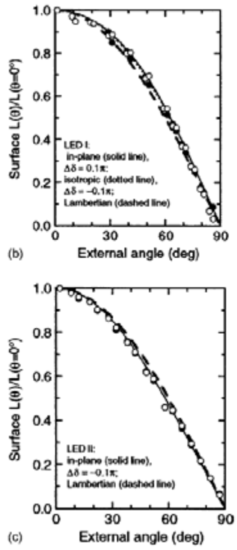
edge-escape $$\theta_2 \le \theta < \theta_3$$

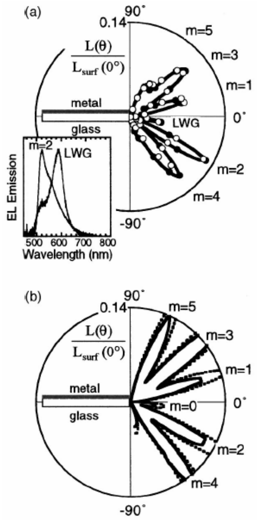


waveguide $$\theta_3 \le \theta < 90^\circ,\ \theta_3 = \sin^{-1}\left(\frac{n_g}{n_p}\right) = 50.8^\circ \text{ if } n_g = 1.55, n_p = 2$$

Ji-Seon Kim, Peter K. H. Ho, Neil C. Greenham, and Richard H. Friend, J. Appl. Phys. **88**, 1073 (2000)

Surface vs edge emission





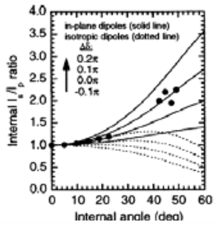


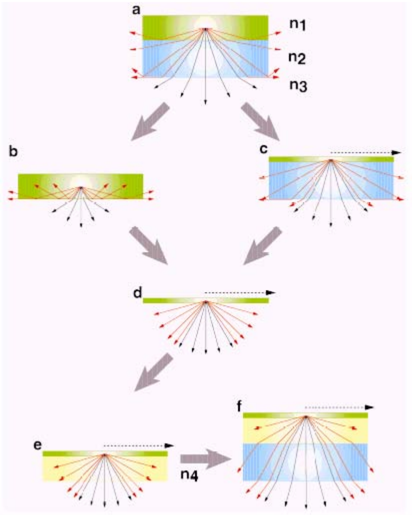
TABLE I. Calculation of the internal EL quantum yield of LED I and II.

	LED I		LED II	
	Calcd[a]	Expt	Calcd[b]	Expt
External F/I_0 (in π sr)				
F_{surf}/I_0	1.03	1.03	0.97	0.97
F_{edge}/I_0	0.88	0.6	0.65	0.4
Internal F/I_0 (in π sr)				
surface-escape zone	1.03	—	0.97	—
no-escape zone	0.45	—	0.37	—
edge-escape zone	1.14	—	0.85	—
waveguide zone	1.44	—	0.88	—
Efficiency calculations				
free-space η_{pl}	—	33%±3%	—	9%±1%
ext (surf) η_{el}[c]	6%	6%±0.5%	1.8%	1.8%±0.2%
ext (surf+edge) η_{el}[d]	11%	9%±1%	3.0%	2.5%±0.3%
int η_{el}[e]	23%	—	5.6%	—

Ji-Seon Kim, Peter K. H. Ho, Neil C. Greenham, and Richard H. Friend, J. Appl. Phys. **88**, 1073 (2000)

Index matching using a thin aerogel layer

Doubling Coupling-Out Efficiency in Organic Light-Emitting Devices Using a Thin Silica Aerogel Layer
T. Tsutsui, M. Yahiro, H. Yokogawa, K. Kawano, M. Yokoyama, Adv. Mater. **13,** 1149-1152 (2001).



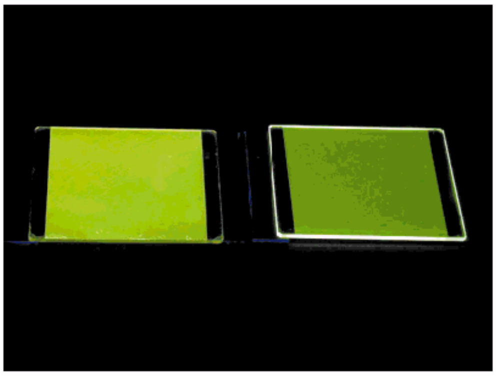
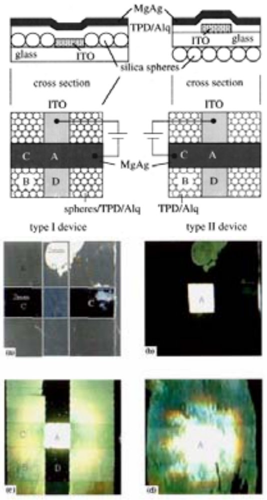
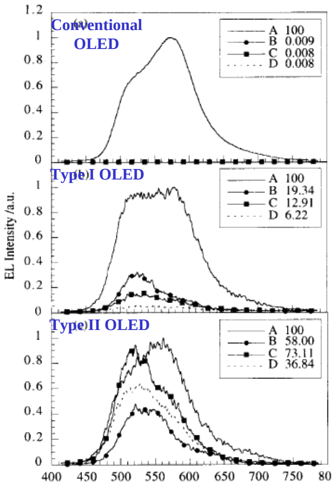
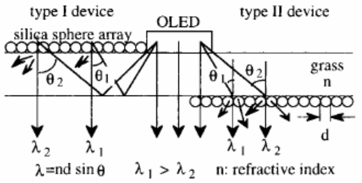


Fig. 3. Photograph of ultrathin emissive layer on glass substrate with (left) and without (right) aerogel spacer layer under UV irradiation. The left picture corresponds to Figure 1f and the right one to Figure 1c. Intense edge emission is observable only in the right sample.

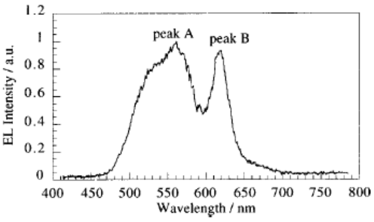
2D ordered array of silica spheres







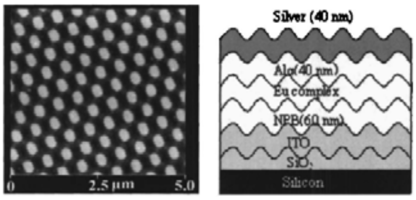
Emission spectra from zone D in the type I device measured directly through a pinhole with a diameter of 0.8 mm.

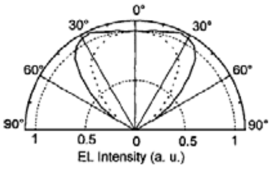


2D ordered array of silica spheres:
Advantage: Waveguiding light components can be taken out from the inside of a device by using scattering.
Disadvantage: Colors due to the scattering are dependent on scattering positions and observation angles.

Takashi Yamasaki, Kazuhiro Sumioka, and Tetsuo Tsutsui, Appl. Phys. Lett. **76**, 1243 (2000).

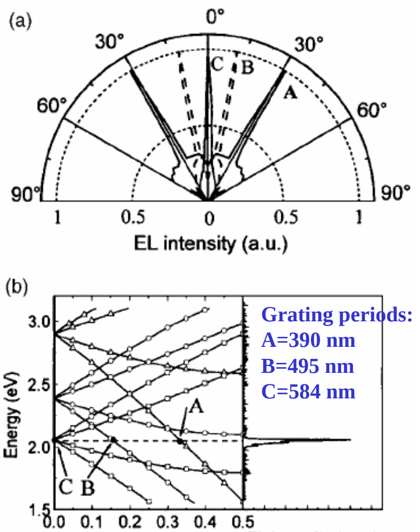
Top-emission OLED with 2D corrugated Ag film as a cathode





Conventional OLEDs with 40-nm-thick (dot) and 60-nm-thick (solid) Eu(DBM)$_3$ layers.

Highly directional EL from 2D corrugated TEOLEDs



Grating periods:
A=390 nm
B=495 nm
C=584 nm

The relation between the emission angle and the wavevector of surface plasmon (SP), ***k***$_{\mathrm{Ar/air}}$,

$$\mathrm{k}_{\mathrm{Ag/air}} + \mathrm{mK}_{\mathrm{x}} + \mathrm{nK}_{\mathrm{y}} = \frac{\omega}{c}\sin\theta \quad \mathrm{m,n} = 0,\ \pm 1,\ \pm 2\ldots$$

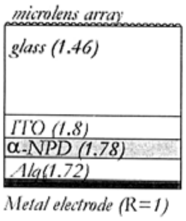
$$\mathrm{k}_{\mathrm{Ag/air}} = \frac{\omega}{c}\frac{\varepsilon(\omega)}{\sqrt{\varepsilon(\omega)+1}}$$

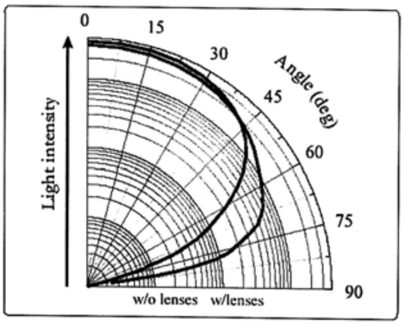
$$\varepsilon(\omega) = \text{dielectric constant of silver}$$

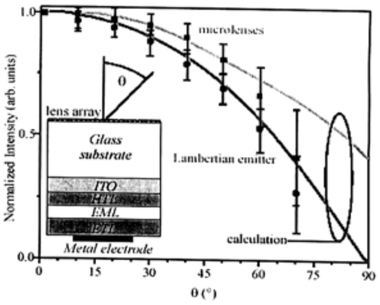
Jing Feng, Takayuki Okamoto, and Satoshi Kawata, Appl. Phys. Lett. **87**, 241109 (2005).

Ordered Micro-lens

- ➢ **External Quantum Efficiency increase up to Factor 2.3**
- ➢ **A Little Improvement of Front Light**



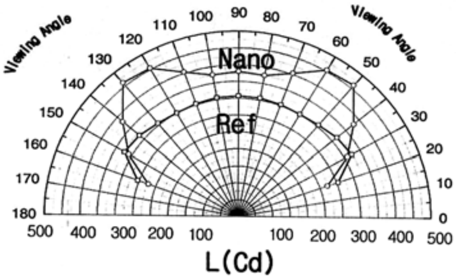




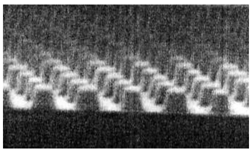
❖ **Source: Princeton University**

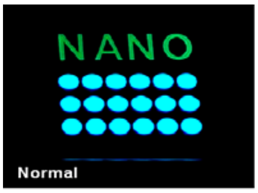
2D Grating Approach (Photonic Crystal)

Best Results: Up to 70% Improvement at the Front Light

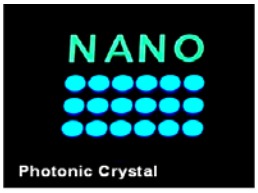


Photonic Crystals





G: 78 cd/m² @100mA



G: 134 cd/m² @100mA

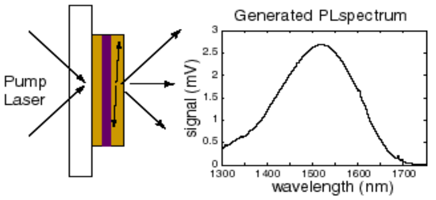
Photonic Crystals

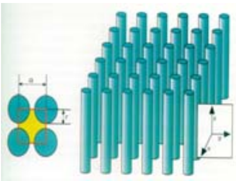
Definition: Periodic spatial variations of the refractive index

Photonic Band Gab (PBG) for certain frequency range of light

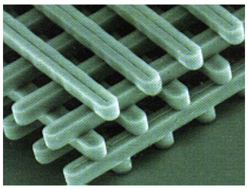
- Butterfly -

Photoluminescence (PL) From Unpatterned Region





2-D Spot structure



3-D Vein Structure

Photoluminescence (PL) From Patterned Region