Electromagnetic modeling of OLEDs and its applications to advanced OLEDs

Chung-Chih Wu*, Chun-Liang Lin, Ting-Yi Cho, Chih-Jen Yang, Yin-Jui Lu
Dept. of Electrical Engineering, Graduate Institute of Electro-optical Engineering,
and Graduate Institute of Electronics Engineering, National Taiwan University,
Taipei, Taiwan, Republic of China
Phone: 886-2-23635251 x346, E-mail: chungwu@cc.ee.ntu.edu.tw

Abstract

General discussions of the optical structures and rigorous electromagnetic modeling of OLEDs will be first given, and then their applications in analyses and designs of various advanced OLED structures, e.g. microcavity OLEDs, tandem OLEDs and top-emitting OLEDs etc., will be reported.

1. Introduction

Further advance of the OLED technology for displays and lighting impose requirements advanced OLED device structures that would give better optical and electrical performances, such as microcavity OLEDs, top-emitting OLEDs, and tandem OLEDs etc.

One major technical issue associated with these advanced OLED structures is how to design their optical structures. In OLEDs, the total thickness of organic layers is of the order of 100 nm and is comparable to the emission wavelength, often giving rather strong microcavity effects. The microcavity effects inherent with OLEDs can spatially and spectrally redistribute emission of devices, and therefore should be considered in any type of OLEDs. Thus in developing advanced OLED technologies, it is necessary to develop rigorous electromagnetic modeling of optical characteristics of OLEDs to accurately analyze dependence of emission characteristics on viewing angles, wavelengths and polarization, and influences of cavity on the transition rate of molecular excited states. In this presentation, general discussions of the optical structures/ electromagnetic modeling of OLEDs will be first given, and then their applications in various advanced OLED structures will be reported.

2. Results

2.1 Rigorous electromagnetic modeling of OLEDs

The rigorous electromagnetic model of OLEDs is established based on the equivalence between the emission of a photon due to an electrical dipole transition and the radiation from a classical electrical dipole antenna, which can take into account losses due to electrodes and absorption. First, we consider the radiation field from a single dipole of particular position, orientation and frequency embedded in a general layered structure (Fig. 1). With plane-wave expansion of the dipole field, the full-vectorial electromagnetic fields generated by a radiation dipole in a layered structure is calculated, from which the distribution of the radiation power into different plane-wave modes and the far-field radiation related to emission of an OLED are obtained (Fig. 2). In the plane-wave expansion, each plane-wave mode can be characterized by an in-plane wave vector k_t, the component of the wave vector parallel to the layer surface. To model emission of a real OLED, one needs to treat the emitting layer as an ensemble of mutually incoherent dipole radiators with distributions in dipole orientations, locations and frequencies. The total emission intensity I from the OLED as a function of the wavelength λ and the viewing angle θ (i.e. $I(\theta,\lambda)$) is then obtained by averaging contributions over these distributions.

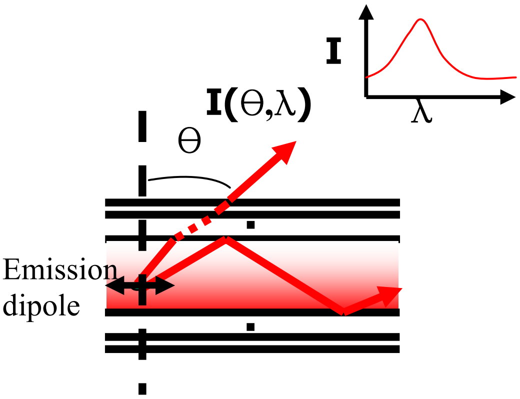

Fig. 1. Schematic diagram of dipole radiation.

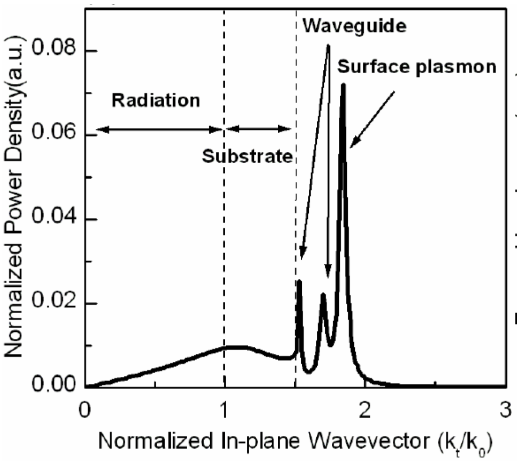

Fig. 2. Distribution of OLED emission into different modes.

2.2 Methodology for optimizing viewing characteristics of top-emitting OLEDs

Top-emitting OLEDs have a few technical merits for active-matrix OLED displays. Generally stronger microcavity effects inherent with top-emitting OLEDs, however, complicate optimization of device efficiency and other viewing characteristics, such as colors and viewing-angle characteristics. Using the rigorous classical electromagnetic model, we analyze emission characteristics of top-emitting OLEDs as a function of device structures. From the comprehensive analysis, trends in the dependence of emission characteristics on device structures are extracted, and accordingly a general methodology for optimizing viewing characteristics of top-emitting OLEDs for display applications will be presented. The effectiveness of the analysis and the methodology is confirmed by experimental results.

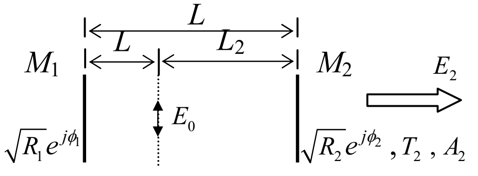

Fig. 3. Schematic structure of a microcavity OLED.

2.3 Examining microcavity OLEDs having two metal mirrors

Incorporation of the microcavity structure into OLEDs is often demonstrated to narrow emission spectra and thus improve color purity for display applications. General complexity and wavelength-selective reflection properties of microcavity OLEDs using dielectric mirrors render difficult their applications in displays, and thus microcavity OLEDs using metal mirrors are considered more practical. However, due to absorption (loss) in metals, it is not clear to what degree and under what conditions one obtains most luminance and color enhancement from such microcavity OLEDs. We examine optical characteristics of microcavity OLEDs having two metal mirrors (Fig. 3) and show that a high-reflection back mirror and a low-loss high-reflection exit mirror are essential for such microcavity devices to obtain luminance/color enhancement relative to conventional noncavity devices (Fig. 4). A luminance enhancement (G_{int}) over 2 in efficiencies has been theoretically and experimentally confirmed for such microcavity OLEDs.

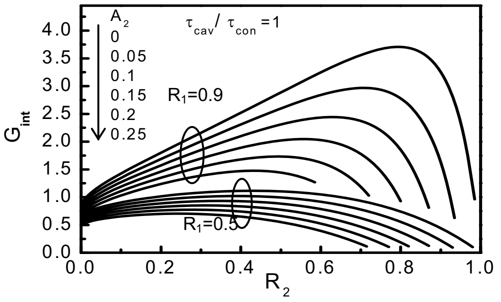

Fig. 4. Luminance enhancement of a microcavity OLED as a function of microcavity parameters.

2.4 OLEDs having emitters at farther antinodes

Due to generally low conductivity and low carrier mobilities of organic materials, OLEDs are typically optimized for light outcoupling by locating emitters around the first antinode of the reflective metal electrode to obtain constructive interference of directly out-going beams with the beams reflected from the metal electrode (i.e. the emitter-to-metal round-trip phase change equals 2π) (Fig. 5). By utilizing device structures containing conductive doping, we investigate theoretically and experimentally the influences of the location of emitters relative to the metal electrode on OLED emission, and show that substantial enhancement in forward luminance (1.6 times) could be obtained by placing emitters around the second antinode instead of the first antinode (Fig. 6). Depending on the detailed condition, the second-antinode device may also give more directed emission as often observed in strong-micrcavity devices yet without suffering color shift with viewing angles and more complicated device structures.

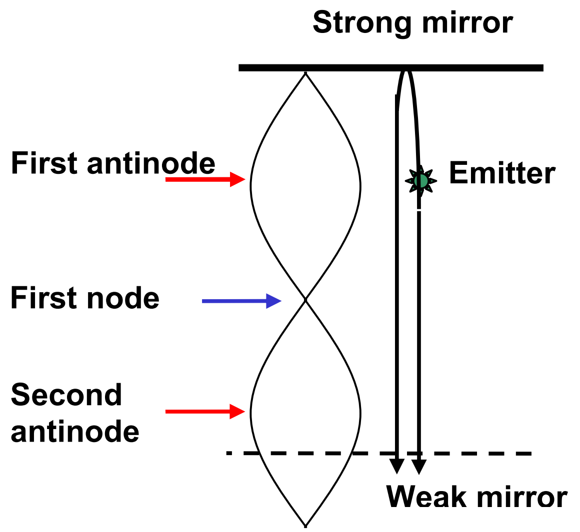

Fig. 5. Schematic diagram showing the location of emitters relative to the reflective electrode in OLEDs.

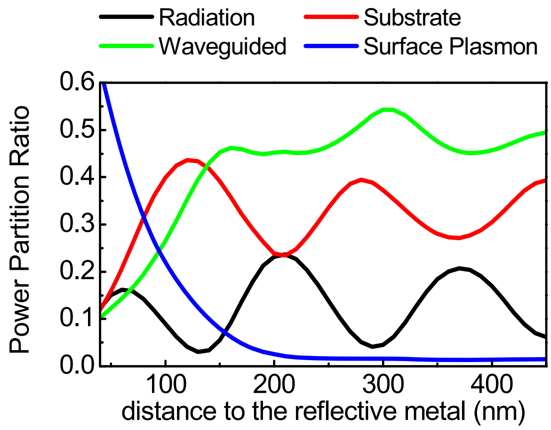

Fig. 6. Distribution of OLED internal radiation into different modes as a function of the emitter-to-reflector distance.

2.5 200-cd/A microcavity two-unit tandem OLEDs

In pursuit of further enhancement in luminance and efficiency of OLEDs, we explore what benefits could be obtained by combining two luminance-enhancement techniques, i.e. microcavity and tandem OLEDs. We investigated theoretically and experimentally the characteristics of noncavity and microcavity tandem OLEDs and show that with well designed microcavity and device structures (i.e. consistent with resonant and antinode conditions), a five-fold enhancement in luminance can be achieved with cavity tandem devices having only two emitting units (Fig. 7). A very high efficiency of 200 cd/A has been demonstrated with a phosphorescent cavity two-unit device (Fig. 8).

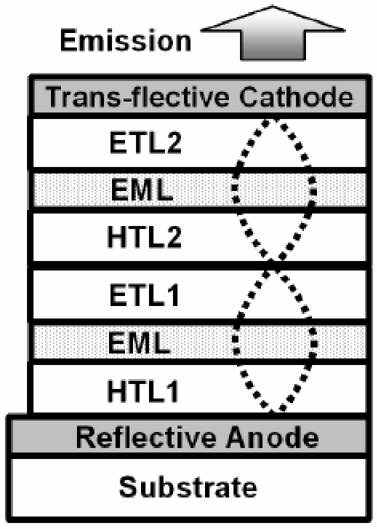

Fig. 7. Schematic structure of microcavity two-unit tandem OLED.

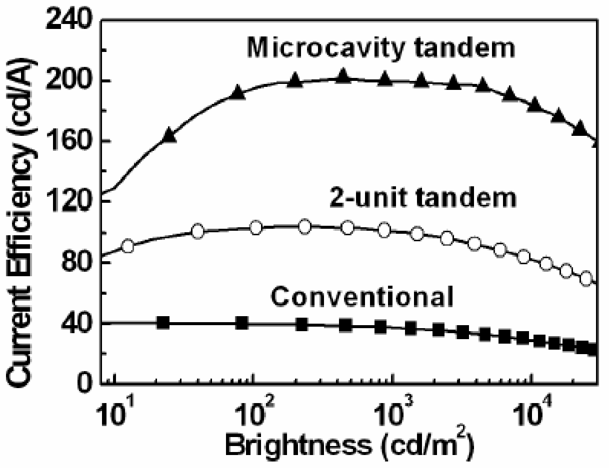

Fig. 8. cd/A efficiencies of various OLED structures.

3. Conclusion

In summary, we have discussed the rigorous electromagnetic modeling of OLEDs for design and analysis of general OLED structures. Its applications to design and optimize advanced OLED structures, such as microcavity OLEDs, tandem OLEDs, top-emitting OLEDs, and second-antinode OLEDs etc., are also given.

4. Acknowledgements

The authors would like to acknowledge financial support from National Science Council of Republic of China. Chun-Liang Lin would also like to thank MediaTek Foundation for the fellowship.

5. References

[1] C.-C. Wu et al, Appl. Phys. Lett.83, 5127, 2003
[2] C.-C. Wu et al, Appl. Phys. Lett.84, 3966, 2004
[3] C.-C. Wu et al, Appl. Phys. Lett.87, 021101, 2005
[4] C.-C. Wu et al, Appl. Phys. Lett.88, 081114, 2006
[5] C.-C. Wu et al, Appl. Phys. Lett.88, 111106, 2006