Enhancing Light Extraction and Viewing-Angle Characteristics in Microcavity TEOLEDs Through Refractive Index Modulation for Surface Plasmon Polaritons Suppression

***Young Rok Kim**, Seung Ju Ok, Thi Na Le and Min Chul Suh**

Department of Information Display, Kyung Hee University,
Kyungheedae-ro, Domgdaemun-gu, Seoul 02447, Republic of Korea.
Email: mcsuh@khu.ac.kr

Abstract

This study improves microcavity OLED performance by tackling viewing angle dependency and efficiency limitations. Integrating a nanoporous film (NPF) and index-matching gel resulted in a 26.36% enhancement in color stability and 14.2% increase in current efficiency. The NPF optimized angular light distribution, while the gel minimized internal reflection losses, enabling stable, high-efficiency OLEDs suitable for large-scale displays and advancing next-generation display technologies.

Author Keywords

Microcavity OLEDs, Top-emission OLEDs, Light Extraction, Viewing Angle Dependence

1. Objective and background

Achieving 100% internal quantum efficiencies (IQE) in organic light emitting diodes (OLEDs) has been challenging. Initially, fluorescent emitters were limited by spin statistics, limiting IQE to 25%. The introduction of phosphorescent materials, utilizing heavy metal complexes, overcame this barrier by harvesting both singlet and triplet excitons, enabling nearly 100% IQEc. [1] However, the high cost of rare metals such as iridium has driven interest in alternative solutions, including Thermally Activated Delayed Fluorescence (TADF) materials, which efficiently utilize triplet excitons without relying on rare metals. [2]

Recent advancements combine fluorescence, phosphorescence, and TADF to improve both efficiency and stability. Hybrid structures integrating these emitters optimize emission spectra and enhance device lifetime. Innovations in triplet exciton management, such as suppressing triplet-triplet annihilation and optimizing charge transport pathways, have further reduced non-radiative losses.

Microcavity structures have also significantly enhanced OLED performance, with the Fabry–Pérot effect. Multi-beam interference within the microcavity amplifies light intensity through phase alignment under specific resonance conditions. The resonance conditions, expressed by key equations, depend on the interference order, cavity thickness (d), and the angle of incidence (θ). These mechanisms selectively amplify light at specific wavelengths, achieving precise color tuning.

Despite achieving 100% IQE, external quantum efficiency (EQE) remains limited to 20–30% due to structural and optical losses. Surface plasmon polariton (SPP) losses occur when light couples with electron-photon waves at the metal-dielectric interface, dissipating as heat. Waveguide modes trap light within organic and Indium tin oxide (ITO) layers or the substrate due to total internal reflection, while refractive index mismatches between organic materials (1.7–2.0) and air (1.0) exacerbate these losses.

To address these challenges, researchers have employed strategies such as refractive index-matching layers, patterned substrates, and microcavity structures to enhance light extraction. Additionally, insulating layers or low-loss conductors at the metal electrode have been explored to mitigate surface plasmon polariton (SPP) losses. These multidisciplinary approaches, integrating device engineering, optical optimization, and material innovation, represent significant efforts to improve EQE and advance OLED performance.[4]

2. Results and Discussion

2.1. Optimization of Green Microcavity TEOLED Devices.

This study explores the suppression of surface plasmon polaritons (SPPs), a primary source of optical losses in microcavity Top-Emission OLEDs (TEOLEDs), which account for nearly 40% of total light loss. By examining the underlying mechanisms of SPP generation and propagation, we aim to optimize the capping layer (CPL) through precise modulation of its dielectric properties. This approach focuses on reducing SPP modes and enhancing light extraction efficiency. The findings are expected to provide a sophisticated design framework for maximizing the performance of microcavity TEOLEDs.

$$L_{SPP} = \frac{1}{2Im(k_{SPP})} \quad (4)$$

$$k_{SPP} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (5)$$

Equation (4) defines the propagation length (L_{SPP}) of surface plasmon polaritons, which quantifies the distance over which the SPPs maintain their energy before significant attenuation occurs. This propagation length is inversely proportional to the imaginary component of the SPP wave vector ($Im(k_{SPP})$). A smaller imaginary component corresponds to lower energy loss and a longer propagation length, making L_{SPP} a critical parameter for evaluating the efficiency of SPP-based light interactions.

Equation (5) provides the expression for the SPP wave vector (k_{SPP}), which governs the behavior of SPPs at the interface between a metal and a dielectric material. It is determined by the angular frequency (ω), the speed of light in a vacuum (c), and the permittivity of the metal (ε_m) and dielectric material (ε_d). This equation highlights how the interaction of the metal's optical properties with those of the adjacent dielectric material influences the SPP characteristics, such as confinement and propagation.

In this study, these equations serve as the theoretical basis for optimizing the capping layer (CPL) above the metal to suppress SPP losses in microcavity TEOLEDs. Specifically, the goal is to

ISSN 0097-996X/25/5603-2197-$1.00 © 2025

reduce the effective dielectric permittivity (ε_d) by increasing the dielectric constant of the CPL. Since the dielectric constant is directly related to the refractive index, this adjustment modifies the refractive index profile at the interface, which, in turn, affects the SPP wave vector (k_{SPP}). By carefully tailoring ε_d, the attenuation rate ($Im(k_{SPP})$) can be minimized, leading to reduced SPP losses and improved light extraction efficiency. To achieve this, we compared two commonly used CPL materials in Top-Emitting Microcavity TEOLED devices: *N*,*N'*-diphenyl-*N*,*N'*-bis(1-naphthyl)-1,1'-biphenyl-4,4''-diamine (NPB, n = 1.8) and Molybdenum oxide (MoO_3, n = 2.1).[5, 6]

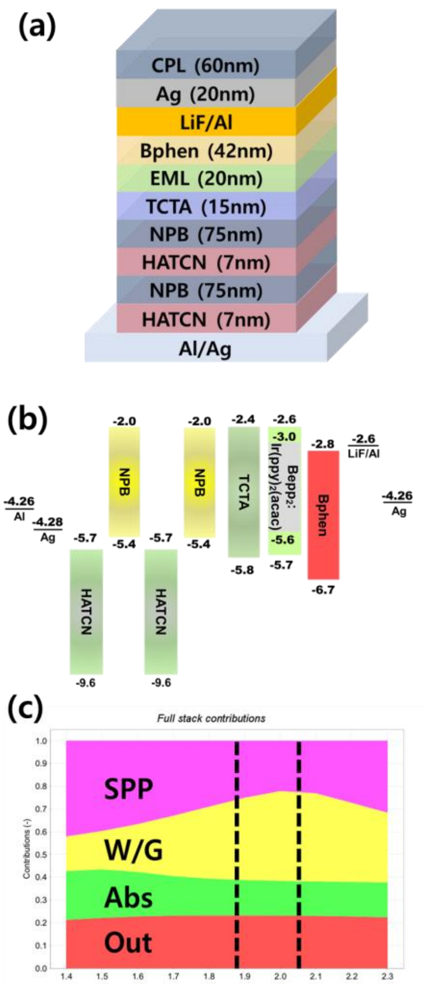


Figure 1. Green microcavity TEOLED capping layer change (NPB, MoO_3) (a) Device Structure (b) Device Structure with Energy Level (c) Mode Analysis simulations using Setfos.

Before conducting the experiments, mode analysis simulations were performed using Setfos, based on the device structures illustrated in **Figure 1(a)** and **(b)**.

The results, summarized in Figure 1(c), showed that the outcoupling efficiency remained largely unchanged, but the SPP mode was reduced by approximately 15%. This reduction aligns with theoretical predictions derived from Equations (4) and (5). Specifically, increasing the dielectric constant of the CPL enhances k_{SPP}, leading to a shorter propagation length (L_{SPP}). Consequently, the contribution of the SPP mode to optical losses is minimized.

Interestingly, the reduction in the SPP mode was accompanied by an increase in the waveguide (WG) mode, which can be attributed to energy redistribution within the device. As the refractive index of the CPL increases, the electromagnetic field's confinement at the metal-dielectric interface weakens, reducing coupling to the SPP mode. Consequently, the energy previously trapped in the SPP mode shifts into the WG mode. The higher refractive index of the CPL enhances its guiding capability, allowing the WG mode to capture energy that would otherwise have been lost to the SPP. Thus, while the reduction of the SPP mode improves light extraction efficiency by minimizing losses at the metal interface, the corresponding increase in the waveguide mode indicates a redistribution of optical energy within the device. These results underscore the critical role of the CPL's refractive index in controlling optical losses and optimizing the performance of microcavity TEOLEDs

2.2. Device properties of Green Microcavity TEOLED capping layer change (NPB, MoO_3).

Based on the previous Setfos simulation results, the device was fabricated using the following structure. The TEOLED was optimized by adjusting the 2nd cavity length between the cathode and anode to enhance the outcoupling of light emitted from the excitons in the device toward the normal direction. The structure of the device is as follows.

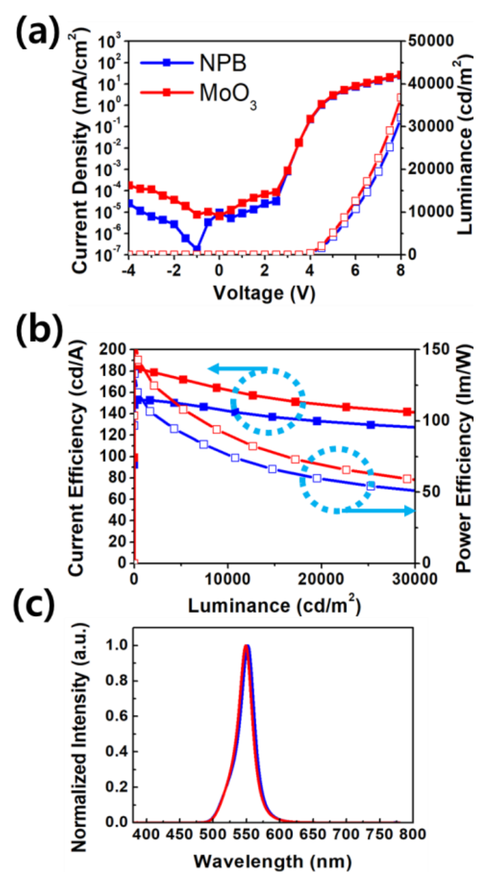


Figure 2. Green microcavity TEOLED capping layer change (NPB, MoO_3) (a) current density and luminance versus voltage (b) current efficiency depends on luminance and power efficiency (c) electroluminescence spectra

Table 1. Properties of Device characteristics based on the differences in Capping Layer (NPB, MoO_3)

Device	V_{on} (V)	J (mA/cm^2) (@ 6 V)	Luminance (@8Vcd/m^2)	C.E. (cd/A) @MAX	P.E. (lm/W) @MAX	λ_{max} (nm)	FWHM (nm)
NPB	3	7.6	32,138	152.6	133.1	551	25
MoO_3	3	8	30,390	181.9	159.3	549	25

Structure of the Green microcavity top-emitting OLED is described as follow: Al(500Å)/ Ag (500Å)/ HATCN (70 Å)/ NPB (750Å)/ HATCN (70Å)/ NPB (750Å)/ TCTA (150Å)/ $Bepp_2$: $Ir(ppy)_2(acac)$ (5%, 300Å)/ Bphen (420Å)/ LiF (7Å)/ Al (8Å)/ Ag (200Å)/NPB, MoO_3 (Capping layer, 600Å)

Figure 2(a)–(c) and **Table 1** summarize the study's results. The current efficiency improved from 152.6 cd/A to 181.9 cd/A, a 19.2% increase. This improvement is attributed to the increase in k_{SPP} caused by the higher refractive index, which reduced L_{SPP} and initially led to a rise in the SPP mode. To mitigate this, a nanoimprinted substrate was introduced to extract and suppress the waveguide (WG) mode. By effectively redirecting the WG mode, the nanoimprint structure enhanced light extraction, significantly contributing to the observed improvement in current efficiency.

2.3. Enhancing Viewing Angle and Efficiency in Microcavity OLEDs Using nanoporous films and Index-Matching Gel.

Microcavity OLEDs face challenges such as changes in color purity and emission spectra with variations in viewing angle. These limitations have confined the application of microcavity TEOLEDs mainly to small and medium-sized displays. For TEOLEDs to be adopted in large displays, improving the viewing angle dependency is a critical challenge.

To address this issue, we introduced a nanoporous film (NPF) as an external device to enhance the viewing angle. The NPF picture is shown in **Figure 3, 4**. The NPF utilizes scattering effects to improve the angular distribution of emitted light. By adjusting the spin-coating speed, the pore size of the NPF was controlled, and its impact on scattering efficiency was analyzed. The results showed that even for microcavity devices with high color purity, the viewing angle distribution became closer to a Lambertian pattern. Additionally, the hypsochromic shift typically observed at wider angles was effectively suppressed.

However, a study by Beom Pyo et al. (Nanoscale, 8(16), 2016) revealed a limitation of the NPF structure, reporting a more than 25% decrease in current efficiency. These findings highlight the trade-offs associated with using NPFs and the need for further optimization to improve viewing angle characteristics while minimizing efficiency losses.

The 25% reduction in current efficiency, as shown in Figure 3(b), is attributed to the presence of air within the NPF layer, indicating that the layer consists of both the NPF and an air gap. This refractive index mismatch between the air and the encapsulation glass causes total internal reflection, as confirmed through Light Tools simulations.

To address this issue, we performed simulations to eliminate the air gap by applying an index-matching gel with a refractive index of 1.5, which closely matches that of the glass. As shown in Figure 5, this approach led to a more than 30% improvement in forward light efficiency, demonstrating a clear enhancement. These results suggest that the application of an index-matching gel can effectively reduce light losses caused by the NPF. Based on these findings, we conducted experiments applying an index-matching gel with a refractive index of 1.5 to the NPF structure to validate the simulation results.[7]

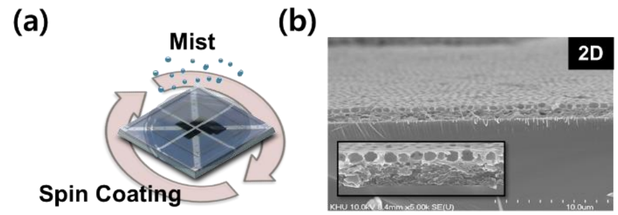
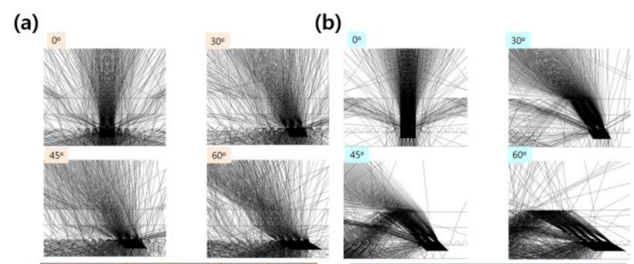


Figure 3. (a) A schematic diagram of the production of Nano porous Film (b) The cross-sectional image of a nanoporous film obtained using a Scanning Electron Microscope (SEM).

Figure 4. Optical micrograph of Nanoporous film (20, 50, 100x)

Table 2. Green microcavity TEOLED with NPF presence or absence of index-matching gel

Device	V_{on} (V)	J (mA/cm^2) (@ 6 V)	Luminance (@8Vcd/m^2)	C.E. (cd/A) @MAX	P.E. (lm/W) @MAX	λ_{max} (nm)	FWHM (nm)
NPF	3	22.4	49,220	141.1	127.0	529	35
NPF + Index Matching Gel	3	19.7	58,874	161.1	141.6	527	34



Angle	0°	30°	45°	60°
Transmittance (%)	57.4	59.7	56.0	54.2
Relative Value (%)	100	104	98	94

Angle	0°	30°	45°	60°
Transmittance (%)	83.6	82.5	58.5	37.9
Relative Value (%)	146	144	102	66

Figure 5. Light Tools simulation results based on the presence or absence of index-matching gel inside the encapsulation glass. (a) without index-matching gel (b) with index-matching gel

Based on the results of the Light Tools simulation, we fabricated devices with the structure shown below.

The structure of the green microcavity top-emitting OLED without index matching gel is described as follows: Al(500Å)/ Ag (500Å)/ HATCN (70 Å)/ NPB (750Å)/ HATCN (70Å)/ NPB (750Å)/ TCTA (150Å)/ $Bepp_2$: $Ir(ppy)_2(acac)$ (5%, 300Å)/ Bphen (420Å)/ LiF (7Å)/ Al (8Å)/ Ag (200Å)/ MoO_3 (Capping layer, 600Å) NPF (2um)

The structure of the green microcavity top-emitting OLED with index matching gel is described as follows: Al(500Å)/ Ag (500Å)/ HATCN (70 Å)/ NPB (750Å)/ HATCN (70Å)/ NPB (750Å)/ TCTA (150Å)/ $Bepp_2$: $Ir(ppy)_2(acac)$ (5%, 300Å)/ Bphen (420Å)/ LiF (7Å)/ Al (8Å)/ Ag (200Å)/ MoO_3 (Capping layer, 600Å) / NPF (2um) + Index Matching Gel

The results are presented in **Figure 6, Table 2**. When the NPF was not applied, the current efficiency was 181.9 cd/A. However, after applying the NPF, the efficiency decreased to 141 cd/A. This decrease aligns with previous reports, where light diffracted by the NPF experienced total internal reflection due to the refractive index mismatch with the air inside the encapsulation glass, resulting in reduced current efficiency.

In contrast, when both the NPF and the index-matching gel were applied, the air gap was eliminated, leading to an improvement in current efficiency to 161.1 cd/A, which closely matches the Light Tools simulation results.

Figure 7 illustrates the color coordinate shift ($\Delta u'v'$) with and without the NPF under varying viewing angles. The shift was 0.0220 without the NPF and 0.0162 with the NPF, representing a 26.36% reduction. This improvement demonstrates the successful fabrication of a more stable device.

3. Conclusion

This study highlights significant advancements in the optimization of green microcavity TEOLEDs through the integration of nanoporous films (NPFs) and index-matching gel. By addressing critical optical loss mechanisms such as surface plasmon polaritons (SPPs) and waveguide (WG) modes, we demonstrated improvements in light extraction efficiency and device performance. The application of a high-refractive-index capping layer reduced SPP modes, while the use of a nanoimprinted substrate effectively suppressed WG modes, achieving a 19.2% increase in current efficiency.

However, the introduction of the NPF alone resulted in a 25% reduction in current efficiency due to total internal reflection caused by the air gap within the encapsulation layer. This limitation was effectively mitigated by applying an index-matching gel, which eliminated the air gap and enhanced light extraction, leading to a 30% improvement in forward light efficiency and a 14.2% recovery in current efficiency.

Furthermore, the combined use of the NPF and index-matching gel significantly improved viewing angle characteristics, reducing the color coordinate shift ($\Delta u'v'$) by 26.36%. This enhancement produced a more stable device with Lambertian-like angular emission. These findings underscore the potential of combining advanced materials and structural engineering to overcome key limitations in microcavity OLEDs, enabling their broader application in large-area displays. Future work should focus on refining these approaches to further optimize the balance between efficiency, stability, and scalability.

4. Impact of Your Research

This study presents significant advancements in microcavity organic light-emitting diodes (OLEDs), addressing key challenges in efficiency, viewing angle stability, and scalability. The incorporation of nanoporous films and optimized capping layers improved light extraction and reduced color shift across viewing angles. These methods offer scalability and economic advantages, aligning with industry demands for cost-effective and sustainable display technologies. The enhanced efficiency contributes to OLED sustainability by reducing energy consumption. This research provides a clear pathway for wider application of microcavity OLEDs in the display industry.

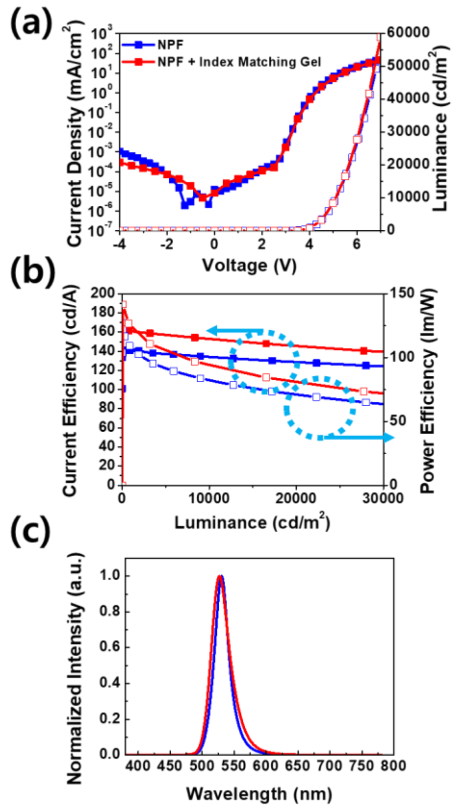


Figure 6. Green microcavity TEOLED with NPF presence or absence of index-matching gel (a) current density and luminance versus voltage (b) current efficiency depends on luminance and power efficiency (c) electroluminescence spectra

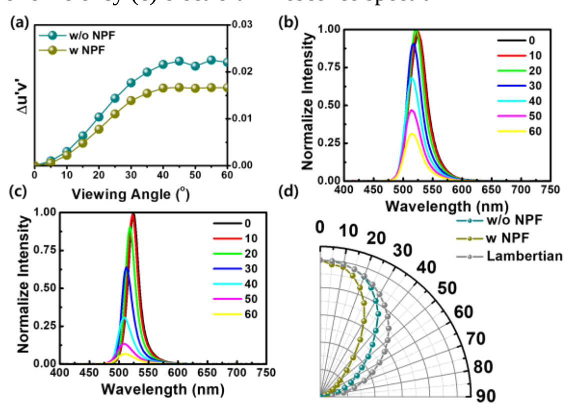


Figure 7. Green microcavity TEOLED presence or absence of NPF (a) color coordinate shift, angular EL spectrum changes from 0 to 60° (b) without NPF (c) with NPF (d) normalized luminance-viewing angle behaviors.

Acknowledgments

R.Y.K, and S.J.O contributed equally to this work. This work was supported by the Industrial Strategic Technology Development Program (20014668, 20011059, RS-2024-00418116, RS-2024-00417913) through KEIT, funded by the Ministry of Trade, Industry and Energy, Korea. It was also supported by Basic Science Research Program through the NRF, by the Ministry of Science and ICT, Korea (2021R1A2C1008725), BK21 Plus Program (21A20130000018,) funded through the NRF by the Ministry of Education, Korea.

References

1. Yang Hee Tae, et al. Advanced Optical Materials, Volume 24, Page 1881(2024)
2. Roh Jiho, et al. ACS Photonics, inpress (2024)
3. Salehi, Amin, et al. Advanced Functional Materials, Volume 29, Page 1808803 (2019)
4. Kim Nam Su, et al."Suppression of viewing angle dependence of organic light-emitting diodes by introduction of circular polarizer with nanoporous polymer film." Organic Electronics, Volume 44, Page 232-237 (2017)
5. Barnes William L, et al. Journal of Optics A: Pure and Applied Optics, Volume 8, Page S87 (2006)
6. Nobuyoshi Hiramatsu, et al. "Propagation length of mid-infrared surface plasmon polaritons on gold: Impact of morphology change by thermal annealing." Journal of Applied Physics, Volume 120, Page 173103 (2016).
7. Pyo Beom, et al. "A nanoporous polymer film as a diffuser as well as a light extraction component for top-emitting organic light-emitting diode with strong microcavity structure." Nanoscale, Volume 8, Issue 16, Pages 8575-8582 (2016).