



Analysis of light out-coupling from microlens array

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ABSTRACT

Microlens array has been known to be effective in enhancing the out coupling efficiency of LEDs, OLEDs and other thin film light emitting devices. However, mechanism of efficiency enhancement by use of microlens arrays is still ambiguous, apart from suggestions that it leads to randomization of photons. We have studied the photon dynamics in the presence of microlens arrays and the effect of various parameters e.g. microlens contact angle, absorption and substrate refractive index using ray tracing simulations. Microlens array leads to extraction of a portion of photons outside the escape cone at the cost of reduced extraction from within the escape cone. The reduced extraction from within the escape cone is compensated by multiple reflections from the back surface. Increase in microlens contact angle reduces the number of reflections required for out-coupling hence reducing the absorption in the device.

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1. Introduction

External efficiency of LEDs, OLEDs and other thin film light emitting devices is limited by the out-coupling efficiency or extraction efficiency. The high refractive indices of the active layer lead to total internal reflection and wave-guiding of a major portion of generated light. The higher the refractive index the smaller is the escape cone defined by the critical angle for total internal reflection. Out-coupling efficiency has been improved by opening of higher number of the six escapes cones for each direction (lateral and vertical) using thick transparent substrates, shaping of LED chips or by reducing wave-guiding through modification of various interfaces in the device [1]. Interface modification induces photon randomization there by giving multiple chances to photons to escape upon subsequent reflections. Photon randomization has been achieved by simple interface roughening [2] or by having regular patterned structures at various interfaces e.g. bragg gratings [3], micro-rings [4], photonic crystals [5], microlenses [6], micro-pyramids [7] etc.

Microlens array, as an external out-coupler, has been shown to increase the efficiency by 1.5 to 3 folds in LEDs and OLEDs [6–24]. Microlens of different diameter, aspect ratio, and area coverage has been applied to improve the out-coupling efficiency. Recently, microlens array has also been used on sapphire substrates to improve GaN epilayer growth and enhance out-coupling in LEDs [25]. Most of these studies describe specific devices with experimental and simulation data on out-coupling enhancement. The mechanism of efficiency enhancement by use of microlens array is still ambiguous, apart from suggestions that it leads to randomization of photons and out-couples some wide angle rays from the substrate layer. Photon randomization,

be it through surface structures like microlens array or surface roughening, all rely on photon redirection and reflection from the back surface. Surface roughening has the advantage of the availability of numerous techniques to roughen surfaces of most materials. Surface roughening has been applied to a wide variety of LED and OLED surfaces, e.g. AlGaAs, AlGaIn, InGaP, GaN, SiC, sapphire etc. But the total random nature of photon dynamics imposes a limit on its efficacy. Regular periodic structures particularly microlens arrays suffer with the disadvantage of not having a versatile fabrication technique applicable to a wide variety of materials. The advantage of microlens arrays over surface roughening is not clear though the systematic dependence of out-coupling enhancement on lens parameter does indicate towards a more organized ray dynamics. The mechanism of out-coupling by microlens arrays needs to be explored to establish its efficacy over other randomization techniques. The use of microlens array not only enhances the light out-coupling but also changes the angular intensity distribution which otherwise is lambertian for a planar device. This work reports on the ray dynamics upon use of microlens array as external out-couplers and the resulting out-coupling and angular distribution through ray tracing simulations.

2. Device and simulation parameters

Fig. 1 shows the schematic of the device simulated in our study. It consists of a high refractive index active layer (thickness, $t \sim 2 \mu\text{m}$, refractive index, $n \sim 1.93$) on a glass substrate ($t = 1 \text{ mm}$, $n = 1.515$). The device size was $2 \text{ mm} \times 2 \text{ mm}$ with reflecting sides. The top surface of the glass substrate was textured with microlens arrays of $20 \mu\text{m}$ diameter with different aspect ratios. The bottom surface of active layer was assumed to have a reflective contact with different absorptions. Fresnel losses were considered at both the substrate–air interface and substrate–active layer interface. In LEDs, OLEDs and thin film phosphor devices, an

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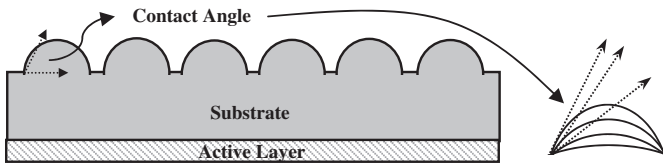


Fig. 1. Device used for ray tracing simulations. The active layer was 2 μm thick where as the substrate was 1 mm in thickness. Top surface of the substrate was covered with microlens array of various contact angles, 20 μm diameter and 58% area coverage.

active layer with high refractive index is grown on a substrate. Typically, the substrate/active layer interface is smooth and the emission from active layer is isotropic. A reflector, either a metallic mirror or a Bragg reflector is put at the bottom of the device. The device in simulation represents a simplified LED/OLED structure. The refractive index, absorption and other material properties will vary with different devices but the fundamentals and ray dynamics will remain similar to that explored using the simulations. Monte Carlo ray tracing simulations were done for a million rays generated with random directionality in the active layer. All simulations were done for light with 593 nm wave length. Out-coupling was measured by placing large detectors close to the surfaces, whereas angular distribution of intensity was determined by placing a far-field detector centered on the glass substrate. Absorption at the interface was realized by proportionally reducing the power of all rays incident on the surface. The rays were split into transmitted and reflected rays at the interface according to the Fresnel equations which were then traced again with non-sequential ray tracing. Both planar and far-field detectors measured the power of the out-coupled rays. Aspect ratio of the microlenses was varied by varying the contact angle between 0 and 90°. Refractive index of the substrate was changed to 1.7 and 1.93 to study the effect of substrate refractive index.

3. Results and discussion

3.1. Effect of microlens contact angle and substrate refractive index

Classically the amount of light transferring from one medium to another has been calculated as the fraction of solid angle subtended by the escape cone at the interface provided the light generation is isotropic in the optically dense medium. It is given by

$$\eta = \frac{1}{2} \left(1 - \sqrt{1 - \left(\frac{n_2}{n_1} \right)^2} \right) \quad (1)$$

where n_1 and n_2 are refractive indices of the medium. Accordingly, a planar device with $n_{\text{sub}}/n_{\text{act}} = 1.5/1.93$ would have 14.4% light out-coupling from top and bottom, 61.9% light wave guided in the active layer where as the rest 23.7% wave-guided in the glass substrate. The out-

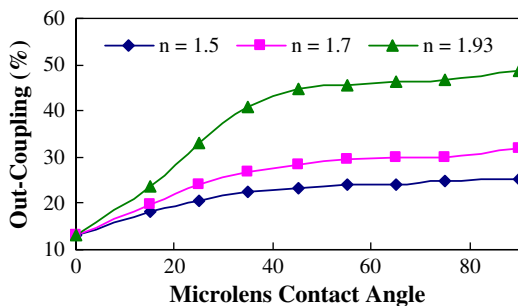


Fig. 2. Out-coupling efficiency with increase in microlens contact angle for different substrate refractive index. Hemispherical microlens array shows maximum efficiency for all substrates.

coupling efficiency increases with the use of external out-couplers and the cumbersome nature of ray dynamics necessitates simulation and experimental studies instead of an analytical approach. Fig. 2 shows the out-coupling efficiency of the device with increase in the contact angle of the microlenses. Initially there is a steep increase in the out-coupling from planar to microlens surface, there after the out-coupling was found to increase linearly with contact angle. As previously reported, maximum out-coupling enhancement was observed for hemispherical microlenses, approximately an increase of 1.35 fold. Möller et al. observed experimentally an increase of 1.5 fold where as their 1D simulation predicted 2.3 times increase [8]. The lower experimental enhancement was reportedly because of the imperfect nature of microlenses whereas the 1D nature of simulation inherently leads to an overestimation of enhancement in efficiency. The experimental enhancement was close to 1.35 fold with some effect of imperfect microlenses. The increase in enhancement came from reduction in wave-guiding in the substrate layer where as the wave-guiding in the active layer remained same. In LEDs and OLEDs, the active layer typically has the highest refractive index and hence leads to substantial wave-guiding losses. Modification of substrate/active layer interface and use of high refractive index substrate are among possible ways of reducing wave-guiding in the active layer. High refractive index substrate would increase substrate mode photons from where it can be out-coupled by use of external out-couplers e.g. microlenses. The increase in out-coupling with different substrates ($n = 1.7, 1.93$) is shown in Fig. 2. The use of high index substrate significantly increased the light out-coupling over lower index substrates for similar contact angle microlenses by reducing the wave-guiding in the active layer. Out-coupling was further increased when the refractive index of the substrate matched with that of the active layer. There would be no wave-guiding specific to the active layer in such a case and the angular intensity at the microlens surface would be isotropic, instead of lambertian. Nakamura et al. studied the effect of substrate refractive index on out-coupling with micro-pyramidal array as external out-coupler [11]. Contrary to our result, substrates with higher refractive index did not show enhanced out-coupling. In a planar device the higher amount of rays in the substrate does not result in efficiency enhancement because of the reduced critical angle (escape cone) at the substrate/air interface. For non-planar substrate/air interface, out-coupling depends on multiple reflections; the decrease in escape cone at the substrate/air interface is more than compensated by multiple reflections from the bottom surface. The lack of enhancement with the use of high refractive index substrate in Nakamura's device was most likely due to high absorption of the reflected rays particularly by the absorptive metal contact.

Fig. 3 shows the ratio of out-coupled power to that of total power in the substrate mode ($\eta_{\text{ext}}/\eta_{\text{sub}}$) for different microlenses and substrates. Since an external out-coupler only helps in extraction of substrate mode rays, the ratio $\eta_{\text{ext}}/\eta_{\text{sub}}$ is a better parameter to determine the efficiency of microlens array. It is interesting to note that higher proportion of substrate mode rays are out coupled when substrate refractive index is low, though the overall out-coupling is higher for high refractive index substrates.

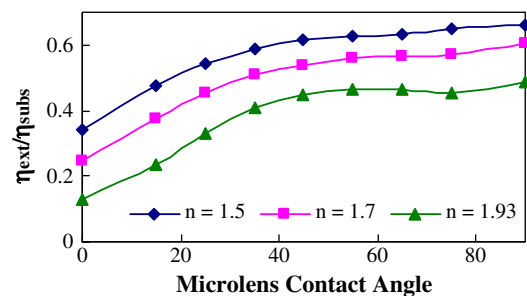


Fig. 3. Enhancement relative to the substrate mode photons for different refractive index substrates. With increase in substrate refractive index, more photons are extracted from active layer mode to substrate mode from where out-coupling is possible because of microlens array.

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