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Modeling of light extraction efficiency of scattering thin film using Mie scattering

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Significant amount of emitted light from an organic light emitting diode (OLED) is trapped as a result of total internal reflection (TIR) on a glass–air interface. One of the strategies to increase the light extraction efficiency is using a scattering thin film. A model is built using the Monte Carlo ray tracing method to simulate Mie scattering. Almost 100% of light trapped by the TIR can be extracted if the radius of the spherical scatters, the refractive index ratio between the matrix and the scatter and the concentration of the scatter are optimized. The implication is important for a high efficiency OLED used in the next generation lighting source.

Keywords: organic light emitting diode, light outcoupling, Mie scattering.

1. Introduction

An organic light emitting diode (OLED) has been recently successfully commercialized in displays. Great effort has been placed on increasing the efficiency, brightness and lifetime of OLED in order to compete with alternative lighting sources. Theoretically, OLED is predicted to be able to reach 100% intrinsic quantum efficiency [1]. Intensive research and development on cheap manufacturing techniques are spear-headed by start-ups and multinational co-operations in an effort to reduce costs comparable to fluorescent lamp [2]. An OLED lighting panel holds promising potential for high efficiency lighting application as part of global effort on reducing carbon footprint. In order to be used as lighting tiles, the colour must be within the Planckian limit and gives a good colour rendering index [3]. About 35% of light is trapped within the OLED devices of which significant amount is the result of total internal reflection from the glass–air interface [4]. This is in sharp contrast with a fluorescent tube where the extraction is near unity. Numerous methods have been implemented to extract the light trapped by the glass–air interface such as microlens arrays [5], antireflection coating [6], photonic crystal [7], moth-eye template [8] and light scattering thin film [9]. The latter seems to be more cost effective to be employed onto the glass substrate due to its mechanical rigidity, stability and low cost fabrication which is for example unlike the moth-eye template where the nanostructures are easily damaged by pressure. Others use microcavity to engineer the emission so that most of the light is emitted at the forward direction below critical angle [10]. However, it is expensive to implement a microcavity OLED if widespread adaptation of this OLED lighting technology is to be realized. Several models have been developed to investigate the trapped photons inside the OLED devices [9, 11, 12].

So far, no work has been done to relate the extraction efficiency of a light scattering thin film on the size of the scattering particles. Here, a model is built to relate the radius, concentration, refractive index of the scattering particles and the matrix to the extraction efficiency.

2. Simulation

Mie scattering theory has been applied to study the distribution of the particle size in fluid [13], in tissue [14], and the time evolution of a sonoluminescence bubble [15], just to name a few. Employing efficient multiple Mie scattering algorithms [16], it is important to study a particulate system as often multiple particles are presented and this would modify the final intensity distribution [17]. Here, we are interested to study the effect of light extraction efficiency of a scattering thin film using Mie scattering [18] with Monte Carlo component in order to determine the optimum system for light extraction.

These complete equations are modeled in C++. Ray tracing is used to trace the path of a photon until it exits to the air. The concentration is varied by changing the number of particles per unit area. Ten thousand of photons are ray-traced in order to obtain the light extraction efficiency which is defined as

$$\eta = \frac{\text{number of outgoing photon}}{\text{number of incoming photon}} \times 100\%$$

The wavelength is fixed at 550 nm throughout all the simulation. A highly efficient OLED usually consists of a multilayer organic thin film with a mirror-like cathode and transparent indium tin oxide (ITO) as an anode [19]. These layers usually have a slightly different refractive index with ITO having the largest refractive index mismatch between the layers [4]. In this simulation, the light extraction of the scattering thin film is modeled as a stacked layer of a mirror-like cathode/glass/light extraction thin film/air as shown in Fig. 1. The glass is assumed to be very thin. The light is seen to be emitted from the bottom of the scattering thin film. The thickness of the glass and the polymer are ignored as it does not undergo scattering because we are interested in finding out the extraction efficiency of a scattering thin film for light trapped by TIR. The thickness of the scattering thin film is 2 mm and the lateral length is 4 mm. The thickness and the lateral length are fixed while the concentrations, particle size and refractive index of the scattering particles are varied. The glass has a refractive index similar to the matrix of the scattering thin film, *i.e.*, 1.55. The stack is assumed to be non-absorptive and the photon is assumed to be scattered from the center of

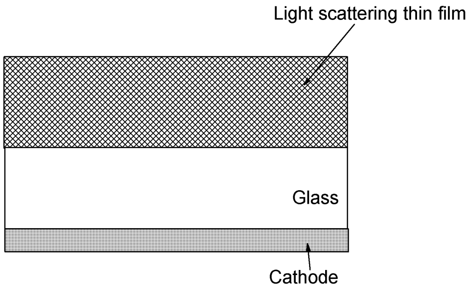

Fig. 1. The cross-section of a modeling device.

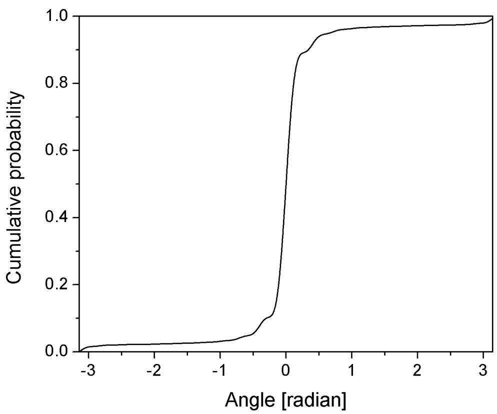

Fig. 2. Cumulative probability versus angle in radian for light scattering of a single particle of radius 1 μm. The computer selects randomly a value between 0 and 1 and the scattered angle can be easily found. Note small scattered angle is preferred.

the particle. In order to relate the refractive index and the size of the scattering particle, transformation of Mie scattering intensity into the probability density function is required rather than using the Henyey–Greenstein scattering function which cannot be related to the particle size. The Mie scattering intensity of the equation of a given particle is computed and normalization gives the probability density function. Transformation of the probability density function into the cumulative probability provides a mean for a program to select a random scattered angle as shown in Fig. 2.

In this model, a photon which has been reflected more than twice from the cathode mirror is ignored. Two-dimensional spatial propagation rather than three is considered in this model as the main results of the model would be equivalent.

Light is assumed to be generated randomly at all angles.

3. Results and discussion

As expected, the free-mean path decreases with increasing concentration of the particles as illustrated in Fig. 3.

It is expected that concentration must play a key role in light extraction efficiency. The concentration of particles inside the scattering thin film as a variable is simulated

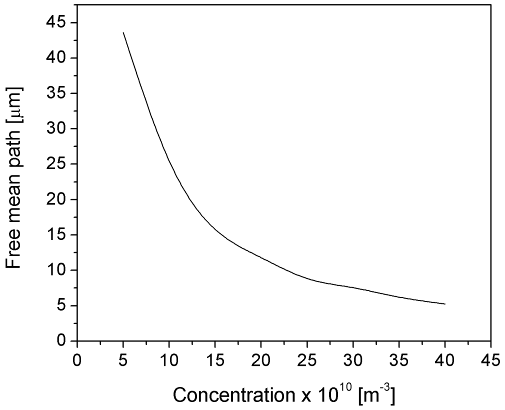

Fig. 3. Free-mean path of the photon versus the concentration. Radius of the scatter r = 1 μm and m = 1.55.

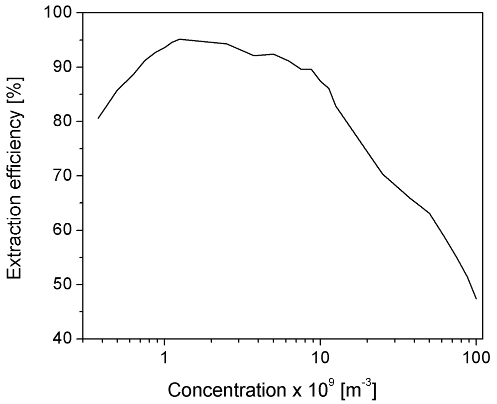

Fig. 4. Light extraction efficiency versus concentration of a scattering film. Radius of the scatter r = 1 μm and m = 1.55.

as depicted in Fig. 4. In agreement with the previous published data [9], there is an optimum concentration of particles for light extraction. The decrease in light extraction efficiency is most likely the result of scattered light being trapped within the scattering thin film and leaked through its edges.

The first simulation suggested the optimum extraction efficiency above 90%. We are interested to investigate the effect of the radius and the refractive index of the particle and matrix on the light extraction efficiency. As shown in Fig. 5, the higher is the refractive index ratio, the poorer is the extraction.

In this simulation, the refractive index of the matrix is fixed at 1.5 with the radius of the particle being 1 μm. Figure 5 suggests that the refractive index difference between the matrix and the particle must be chosen carefully in order to optimize the light extraction efficiency.

An ideal scattering thin film is such that it can scatter light at an angle less than the critical angle as defined by its matrix. If the incident light travelling into the scat-

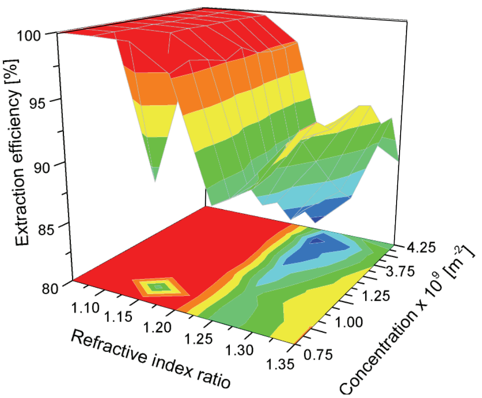

Fig. 5. 2D mapping of refractive index ratio and concentration. A strong dependence of refractive index ratio on light extraction efficiency. Radius of the scatter $r = 1$ µm.

tering thin film is larger than the critical angle and if the particle is ineffective in scattering the photon from its original path, as it is happening with the light scattering thin film of a higher refractive index mismatch between the matrix and the particle, then, intuitively, the light extraction will decrease. This provides an explanation of a decrease in the light extraction efficiency when the refractive index ratio increases.

Next, the radius of particles is varied for a different refractive index ratio as shown in Fig. 6.

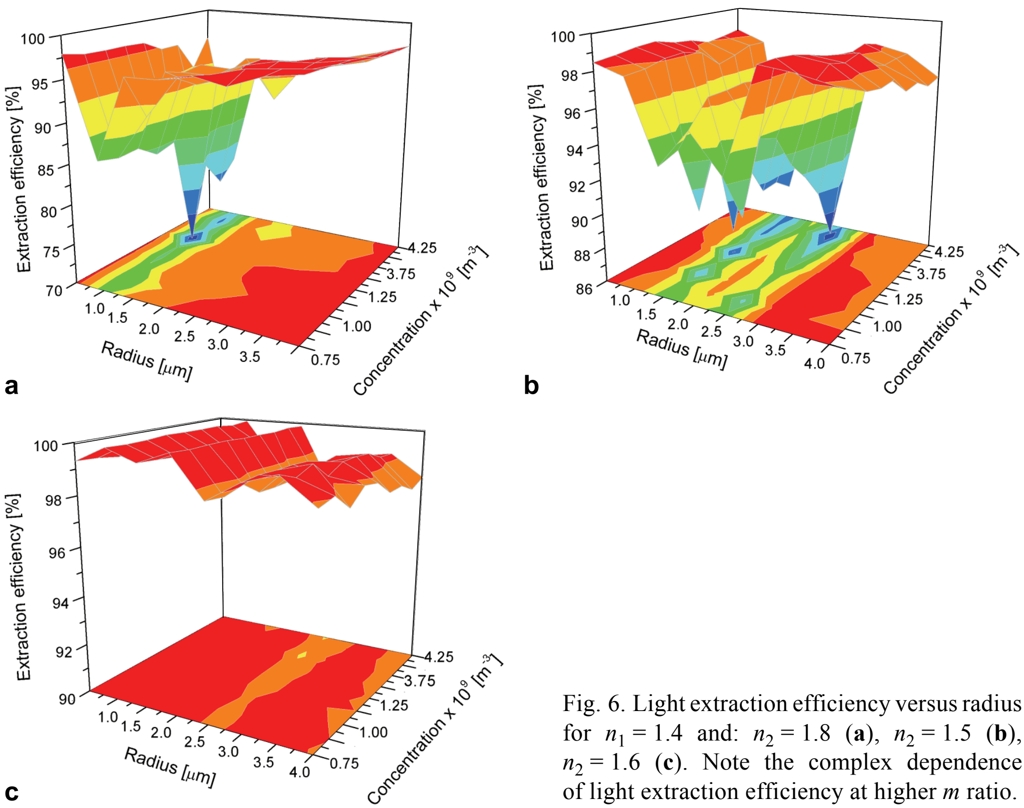

Fig. 6. Light extraction efficiency versus radius for $n_1 = 1.4$ and: $n_2 = 1.8$ (**a**), $n_2 = 1.5$ (**b**), $n_2 = 1.6$ (**c**). Note the complex dependence of light extraction efficiency at higher m ratio.

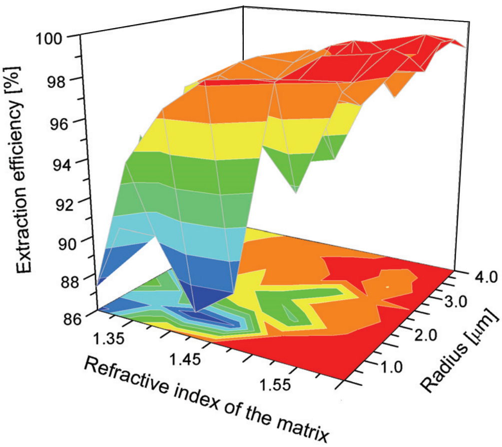

Fig. 7. Light extraction efficiency versus the refractive index of the matrix for radius of particle of 1 μm for $n_2 = 1.8$.

There is a complex dependence of the radius of a particle for a higher value of *m*. It comes with a surprise and we could not find an intuitive reason for it. It might be attributed to the small scattering loop often accompanied by a single particle.

One would expect that the higher the refractive index of the matrix, the poorer is the extraction efficiency as a result of TIR of the matrix. However, Fig. 7 shows otherwise. For $n_2 = 1.8$, it seems that the extraction efficiency strongly depends on the refractive index ratio.

Although the light extraction efficiency can be near 100%, it must be noted that it does not translate into an increase in light outcoupling by a factor of 3 when it is applied on a real OLED device as the emission of OLED devices are influenced by a weak microcavity effect of its planar multilayer [20] where the emission is not Lambertian. Furthermore, some of the emission is waveguided within the polymer which cannot be extracted using the light scattering thin film. However, it is safe to say that the scattering thin film can be used to extract almost all of the light which is trapped by TIR between a glass–air interface.

4. Conclusions

The refractive index ratio and the concentration of the scattering particle in a thin film are found to be very important parameters to obtain a high extraction ratio. The radius of a particle exerts little influence once the two parameters are optimized. In short, it is possible to extract almost 100% of light trapped by TIR using this method.

References

[1] ADACHI C., BALDO M.A., THOMPSON M.E., FORREST S.R., *Nearly 100% internal phosphorescence efficiency in an organic light-emitting device*, Journal of Applied Physics **90**(10), 2001, pp. 5048–5051.

[2] JIN JANG, SUNGKYOO LIM, MYUNGHWAN OH, *Technology development and production of flat panel displays in Korea*, Proceedings of the IEEE **90**(4), 2002, pp. 501–513.

[3] KAI LIN WOON, *CIE 1931 colour space movement of organic light emitting diode*, Optoelectronics and Advanced Materials: Rapid Communications **4**(2), 2010, pp. 121–124.

[4] FRANKY SO, JUNJI KIDO, BURROWS P., *Organic light-emitting devices for solid-state lighting*, MRS Bulletin **33**(7), 2008, pp. 663–669.

[5] MOLLER S., FORREST S.R., *Improved light out-coupling in organic light emitting diodes employing ordered microlens arrays*, Journal of Applied Physics **91**(5), 2002, pp. 3324–3327.

[6] SAXENA K., MEHTA D.S., RAI V.K., SRIVASTAVA R., CHAUHAN G., KAMALASANAN M.N., *Implementation of anti-reflection coating to enhance light out-coupling in organic light-emitting devices*, Journal of Luminescence **128**(3), 2008, pp. 525–530.

[7] YOUNG RAG DO, YOON-CHANG KIM, YOUNG-WOO SONG, YONG-HEE LEE, *Enhanced light extraction efficiency from organic light emitting diodes by insertion of a two-dimensional photonic crystal structure*, Journal of Applied Physics **96**(12), 2004, pp. 7629–7636.

[8] YOON-CHANG KIM, YOUNG RAG DO, *Nanohole-templated organic light-emitting diodes fabricated using laser-interfering lithography: Moth-eye lighting*, Optics Express **13**(5), 2005, pp. 1598–1603.

[9] BATHELT R., BUCHHAUSER D., GARDITZ C., PAETZOLD R., WELLMANN P., *Light extraction from OLEDs for lighting applications through light scattering*, Organic Electronics **8**(4), 2007, pp. 293–299.

[10] SANG-HWAN CHO, YOUNG-WOO SONG, JOON-GU LEE, YOON-CHANG KIM, JONG HYUK LEE, JAEHEUNG HA, JONG-SUK OH, SO YOUNG LEE, SUN YOUNG LEE, KYU HWAN HWANG, DONG-SIK ZANG, YONG-HEE LEE, *Weak-microcavity organic light-emitting diodes with improved light out-coupling*, Optics Express **16**(17), 2008, pp. 12632–12639.

[11] SHIANG J.J., DUGGAL A.R., *Application of radiative transport theory to light extraction from organic light emitting diodes*, Journal of Applied Physics **95**(5), 2004, pp. 2880–2888.

[12] GREINER H., *Light extraction from organic light emitting diode substrates: Simulation and experiment*, Japanese Journal of Applied Physics Part 1 **46**(7A), 2007, pp. 4125–4137.

[13] WEINER I., RUST M., DONNELLY T.D., *Particle size determination: An undergraduate lab in Mie scattering*, American Journal of Physics **69**(2), 2001, pp. 129–136.

[14] WILSON J.D., FOSTER T.H., *Mie theory interpretations of light scattering from intact cells*, Optics Letters **30**(18), 2005, pp. 2442–2444.

[15] WENINGER K.R., EVANS P.G., PUTTERMAN S.J., *Time correlated single photon Mie scattering from a sonoluminescing bubble*, Physical Review E **61**(2), 2000, pp. R1020–R1023.

[16] RIEFLER N., WRIEDT T., *Intercomparison of inversion algorithms for particle-sizing using Mie scattering*, Particle and Particle Systems Characterization **25**(3), 2008, pp. 216–230.

[17] JONSSON J.C., SMITH G.B., NIKLASSON G.A., *Experimental and Monte Carlo analysis of isotropic multiple Mie scattering*, Optics Communications **240**(1–3), 2004, pp. 9–17.

[18] VAN DE HULS H.C., *Light Scattering by Small Particles*, Dover Publications, 1981, pp. 114–128.

[19] D'ANDRADE B.W., BROOKS J., ADAMOVICH V., THOMPSON M.E., FORREST S.R., *White light emission using triplet excimers in electrophosphorescent organic light-emitting devices*, Advanced Materials **14**(15), 2002, pp. 1032–1036.

[20] BULOVIC V., KHALFIN V.B., GU G., BURROWS P.E., GARBUZOV D.Z., FORREST S.R., *Weak microcavity effects in organic light-emitting devices*, Physical Review B **58**(7),1998, pp. 3730–3740.

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