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The Estimation of Enhanced Outcoupling for OLEDs with Isotropically Scattering Materials

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Abstract**—** *This manuscript uses classical geometrical optics and the convergence of an infinite Fourier series to derive a mathematical equation for the out-coupling efficiency of classical scattering-enhanced OLEDs. Several simple assumptions are made regarding how light interacts with scattering media. It describes the extent of efficiency improvement in terms of nanoparticle properties and the revised out-coupling efficiency limitation. The albedo is the ratio of scattering to extinction cross-sections, where extinction is scattering plus absorption. Albedo indicates how much of the light that interacts with a particle is re-emitted or retained to move around the OLED device further. An estimation of the out-coupling efficiency observed when nanoparticles of various albedo values are incorporated into the simplified OLED structure is performed.*

Keywords**— organic light emitting diodes (OLEDs), outcoupling efficiency, plasmonics, scattering.**

I. INTRODUCTION

The basis for incorporating scattering particles into the OLED is to bypass total internal reflections (TIR). The scattering particles reorient the distribution of light Poynting vectors approaching the interface from ones that would have not have left the device, 'super-critical' angles with respect to surface normal, to those that will leave the device, 'sub-critical' angles. However, there is still much fundamental research to be done in the material and exact geometry selection of the nanoparticle scattering material. Scattering media may be metallic or non-metallic, and each modality presents a different scattering mechanism. Silver is commonly known to be a material with one of the highest scattering capabilities per unit volume.

Since a scattering layer that redistributes organic-glass modes is necessary within the charge transport layers of the device structure electrical conductivity is of great importance. The Mie theory introduced in a manuscript of the near future is valid within the quantum limit of particles and light interactions. Mie theory applies to both metallic and non-metallic particles in this limit. The advantage to TiO_2 particles is their lack of imaginary index and therefore expected absorptions

The non-metallic scattering media, such as titanium dioxide, are quite obviously advantaged over metallic ones in the classical limit of particle sizes. In this case, when light interacts with the particle Snell's law refocuses the light. The limitation in their effectiveness is due to the large particle diameters required to significantly bend the rays and alter their path. The refractive index of the particle is chosen such that the light at high angles of incidence bends inside the particle. It then bends again at the interface of the other side of the particle and external media it is embedded in. This scattering phenomenon is solely the result of geometrical optics. Many researchers believe that if the refractive index is selected carefully, then more light will be scattered into the exit cone than out of it. This has been demonstrated in several examples with OLEDs via increased out-coupling factors[1].

In this manuscript, a model is assumed for the scattered field from plasmonic particles and a method to account for the increased extraction due to this scattered field is discerned. This model takes into account the wavelength dependent absorption processes for these particles, dubbed the retention factor (R) or, equivalently, albedo. Albedo is the ratio of scattered light to extincted light. R is estimated for these devices through use of an analytical solution to Maxwell's equations, also detailed in this chapter.

It will be determined if the use of scattering media will overcome the limits defined by total internal reflection to achieve higher out-coupling efficiency devices. Returning to the estimation of the total fraction of the light expected to escape, by introducing an additional high index glass layer into the device structure all of the light can pass into such a glass layer, i.e. no critical angle between the organics and glass, the scattering particles could, then, be embedded into this higher index glass layer. The critical angle at the glass-air interface would then be smaller, and have less light

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escape, than that of the glass-air without the scattering layer had a lower index glass layer been utilized. As such, it will be important to understand how scattering alters the assumed squared sinusoidal distribution of light approaching the interface.

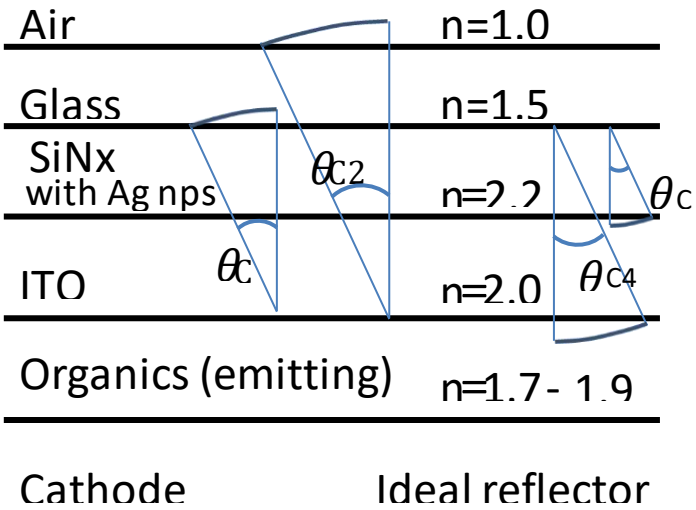

Fig.1: This image is similar to the simplified OLED structure. However, a high index SiNx-type scattering layer with silver nanoparticles has been embedded in between the organic layer and the glass layer. Each interaction of the TIR light with a silver nanoparticle will scatter a portion of that light into the exit cone. θ1 corresponds to the organic-air exit cone. θ2 corresponds to the organic-glass exit cone. The exit cones designated are θ3 and θ4 correspond to the SiNx-ITO and the SiNx.

A. Isotropic Surface Plasmon Resonance Scattering Particles. In metallic scattering-such as in nanoparticles of silver, gold, copper, titanium and chromium- the surface plasmon effect dominates scattering behavior. The surface plasmon effect is a local charge separation on the surface of the nanoparticle, *whereby the electric field of the impinging light is significant enough to drive the electrons to one side of the particle. This creates a surface dipole. When the surface dipole relaxes, it mimics the function of an antenna, and radiates electromagnetic radiation in the visible spectra. The exact nature of the surface dipole and its relaxation are known to be somewhat dependent upon the dielectric properties of the medium into which the particle is embedded[2]. The spatial and time dependence of emitted radiation in response to dipole charge oscillation has been readily measured[3]. In metals it is the topic of current studies. One idea is that the particles are small enough that light entering them is subjected to minimal Beer-Lambert type absorptions.*

The above image depicts light generated by a small molecule emitting isotropically. It is limited in its extraction by the geometrical optics as discussed previously by Forrest et al. When scattering media are added into an adjacent layer, there will be an altered distribution of the light approaching the glass interface. The interaction of the emitted light with the isotropic scattering particles will redistribute the light such that it is not equal over all solid angles as "seen" by a point in the interface. The light that is scattered by the particles will make the luminous flux vary less with respect to the angle of incidence. It will vary more linearly with respect to the angle from the interface surface normal. When light interacts with a particle its associated energy will be redistributed over the surface of the particle and re-emitted. The electric field that results from scattering shall be known as the scattered field. A portion of this scattered field will be lost to absorption, which is accounted for by the albedo. An estimation for the albedo factor will be made later in a separate work. Only a certain fraction of the scattered field will be at wave vectors that are within the exit cone. For spherical particles, this fraction is the same as the TIR case from a previous study for an isotropic emitting molecule: η_C.

The fraction of light that escapes overall can be written as a function of a pass number and the time domain can be neglected. The pass number is simply a way to approach how many times that a light ray interacts with a scattering particle and approaches the extraction interface within the exit cone. The zero-th pass is the direct emission from the organic molecule and determined by the previously defined $\eta_C=1-\text{Cos}[\theta_C]$. The sum of the total internal reflection contributions and the scattered contributions to the complete out-coupling efficiency shall be denoted, $\eta_{C,TIR}$.

The fraction of light that will exit the device as a function of pass number greater than zero, denoted n, is:

$$\eta_{C,Scat}=(1-\eta_{C,TIR})^n R^n \eta_{C,TIR} \quad (1)$$

In the above equation R is the albedo: the fraction of the light that is scattered out of the light extincted by the particle. $\eta_{C,TIR}$ is the out-coupling efficiency of the unenhanced device. After each pass, the fraction of the isotropically scattered light that hit the particle which is within the exit cone escapes and contributes to the out-coupling efficiency. Extinction is the sum as scattering and absorption. In a sense, it is the fraction of the light that interacts with the particle and is retained. Determining the total light extracted with a ray that must interact with such a nanoparticle is done by summing this function as n goes to infinity. For particles that scatter more forward or backward, this model will overestimate the out-coupling efficiency.

This pattern can be described by an infinite, geometric series denoted $\eta_{C,Scat}$:

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$$\eta_{C,Scat} = \sum_{n=1}^{\infty} (1 - \eta_{C,TIR})^n R^n \eta_{C,TIR} \quad (2)$$

$$\eta_{C,Scat} = \frac{n_2{}^2 R + n_1{}^2 \left(-1 + \sqrt{1 - \frac{n_2{}^2}{n_1{}^2}}\right)(1+2R)}{n_1{}^2 \left(-1 + \sqrt{1 - \frac{n_2{}^2}{n_1{}^2}} R\right)} \quad (3)$$

This equation does not account for the expected drop in out coupling efficiency for low albedo particles, and should not be applied to such situations. This scenario would decrease the overall out coupling below the TIR case.

For different values of R and $\eta_{C,TIR}$, this out-coupling factor is plotted:

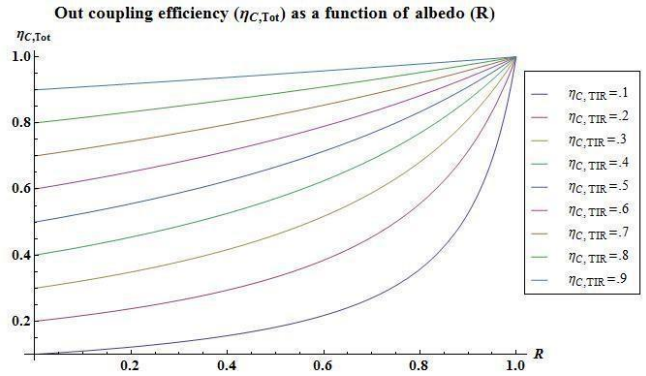

Fig.2: The out-coupling factor for isotropic scattering particles as a function of the critical angle escape fraction and the particle albedo. This figure indicates that even for eta equal to .1, the EQE can reach .5 for R greater than .9.

The out-coupling efficiencies of note are 18.5% for the organic-air cone and 48.5% for the organic-glass cone. In both cases, a reasonably high total out-coupling can be achieved as long as the scattering albedo is high enough. For the smaller exit cone of these two with an albedo of .8, extraction can reach 55%. For the larger exit cone of these two, with an albedo of .8, extraction can reach 80%.

This model assumes that the light ray interacts with a nanoparticle in each pass through the device and that they are embedded in a layer that may add to the thickness of the device. The key is that the particles are in a layer that is refractive index matched or of higher index than the emitting layer such as not to insert a reflection limitation on the out-coupling factor before the light has an opportunity to interact with the nanoparticles. Such a layer would be made of a material such as SiN_x which has a higher index than ITO.

Conclusions

Within this work, an equation for the out-coupling efficiency of scattering-enhanced OLEDs is derived as a function of the refractive index of the organic layers and the light retention capability of the scattering media. Future studies should seek to quantify the light retention capability and angular redistribution properties of small metallic and non-metallic nanoparticles.

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