Numerical Investigation of a 2D-Grating for Light Extraction of a Bottom Emitting OLED

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ABSTRACT
An important limiting factor for efficient white light emitting organic LEDs is the total internal reflection occurring at each interface. In a bottom emitting OLED light is trapped by reflection at the interface between the organic layers and glass substrate and at the interface between the glass substrate and air. We investigate the use of a grating at the glass substrate-air interface. In this paper we will discuss the developed 3D-simulation method and several important simulation results. Our simulation method shows that the grating extracts approximately 50% more power in comparison with a planar device. These results are comparable with the use of micro lenses.
Keywords: extraction efficiency, organic LED, bottom emitting, Bragg grating.

1. INTRODUCTION

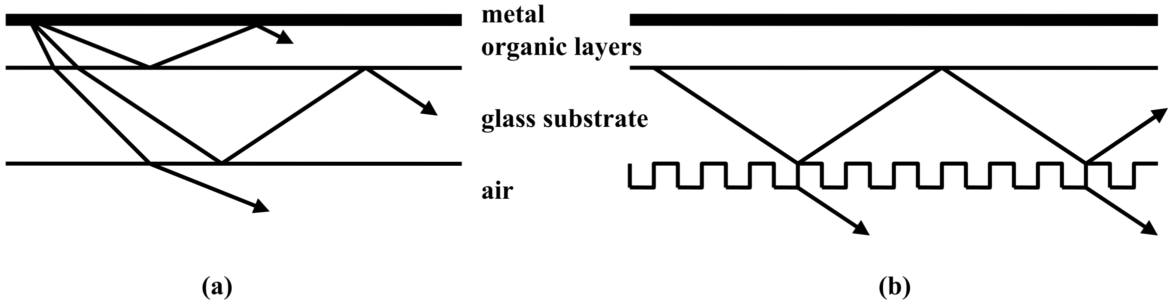

Figure 1. Extraction of light which is trapped for a planar structure.

Organic LEDs (OLEDs) are a promising technology for future lighting [1]. A key requirement for these planar lighting devices is having high brightness at reasonable efficiency or equivalently put, reasonable luminous efficacy. Increasing this efficiency is achieved by maximizing the amount of created excitons, by maximizing the radiative decay of these excitons into photons and by maximizing the amount of light which can escape an OLED device, [2]. Most of these created photons are trapped in the oLED by total internal reflections (TIR). Taking into account the refractive indices of organic layers ($n \approx 1.7$), glass ($n \approx 1.5$) and air ($n \approx 1.0$), we see that TIR occurs at the interface organic layers-glass substrate and glass substrate air, figure 1.a.

Deposition of the organic layers on a corrugated substrate has been proven to increase the efficiency for a photoluminiscent (PL) OLED [3]. Using a periodic grating at the organic layer-glass substrate interface increases out coupling for both electroluminescent (EL) and PL devices, [4] and [5]. Numerical calculations indicate an intermediate layer between organic layers and glass substrate can also improve efficiency [6]. Experimentally it has been proven that an aerogel intermediate layer increases efficiency for EL devices [7]. To eliminate the total internal reflection occurring at the glass substrate-air interface the use of microlenses [8] and a diffusive layer has been investigated [9]. Methods at the glass substrate-air interface are unable to extract light trapped in the organic layers. These methods still increase the extracted light with an additional 50% compared to a planar device.

Our alternative to these last 2 methods is the use of a grating at the glass air interface. The period of this grating is of the same order as the wavelength. The advantage of this method compared to micro lenses is the much smaller size of the grating features.

The following sections will discuss simulation method, simulation results and the conclusion.

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2. SIMULATION METHOD

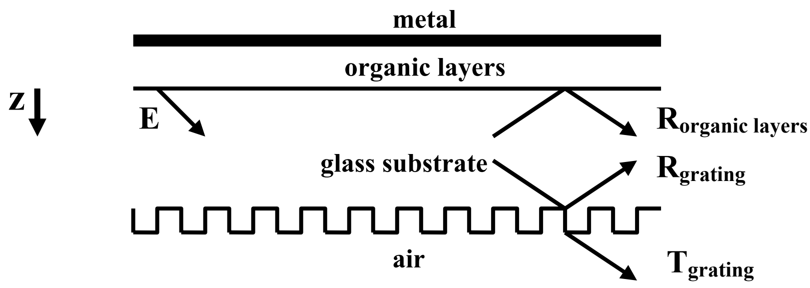


Figure 2. Matrix description of the power flux in z-direction.

With our method we determine the efficiency of a grating placed at the glass-air interface. An extraction efficiency of 100% corresponds with an extraction of 100% of all the light which is injected into the glass substrate. All light injected in the glass layer escapes into air.

The efficiency is defined as the net power flux in air proportional to the net power flux in the glass substrate. The power flux is the power flux through an elementary surface perpendicular to the z-direction.

Our model takes into account following effects: the angular distribution of both emission and absorption of the organic layers, the multiple Bragg diffraction orders and the spatial incoherent multiple reflections of figure 1.b. Spatial incoherence is assumed because the glass is thick compared to the coherence length of spontaneous emitted light.

A key element of this method is the decomposition of the radiating dipole into plane waves. This plane wave expansion calculates the electromagnetic field in the micro cavity composed by the organic layers [10]. The emitted power flux, **E**, and power reflectance of the cavity organic layers, $\mathbf{R}_{\mathbf{organic\ layrers}}$, are a direct result of this calculation. Each of the resulting plane waves is propagated through the OLED structure to find the required efficiency. We have to take into account the power flux of all reflected and transmitted plane waves at each interface. Using the power flux automatically ensures the spatial incoherence of our model.

The effect of the grating on the reflected and transmitted Bragg orders can be calculated with Rigorous Coupled Wave Analysis as used in [11]. The wave vector of the plane wave incident on the grating is $(k_{x,0}, k_{y,0}, k_{z,0})$ **.** The wave vector of all Bragg orders satisfy:

$$\begin{aligned} & k_{i,j} = (k_{x,i}, k_{y,j}, k_{z,i}) = (k_{x0} + ik_{\Delta,x}, k_{y0} + jk_{\Delta,y}, \sqrt{k^2 - k_{x,i}^2 - k_{y,i}^2}) \\ & i, j \in \mathrm{Z} = \{\ldots, -2, -1, 0, 1, 2, \ldots\} \\ & k_{\Delta,x} = 2\pi / x - period, k_{\Delta,y} = 2\pi / y - period \end{aligned} \tag{1}$$

Only diffraction orders with a real $k_{z,i}$ are plane waves with a non-zero power flux. All plane waves which satisfy equation (1) for a certain $(k_{x,0}, k_{y,0})$ form a set. We can place the reflection of the diffraction orders for any incident plane wave which satisfies (1) in one of the column of the square matrix $\mathbf{R}_{\mathbf{grating.}}$ The power transmission of the flux can be written in an n dimensional array $\mathbf{T}_{\mathbf{grating}}$.
For any set of power carrying Bragg orders we write.

$$\begin{aligned} \text{total flux for one set} &= \mathbf{T}_{\mathbf{grating}}.\mathbf{E} + \mathbf{T}_{\mathbf{grating}}.\ \mathbf{R}_{\mathbf{organic\ layers}}\ \mathbf{R}_{\mathbf{grating}}\ \mathbf{E} + \mathbf{T}_{\mathbf{grating}}.\ (\mathbf{R}_{\mathbf{organic\ layers}}\mathbf{R}_{\mathbf{grating}})^2\ \mathbf{E} + \ldots \\ &= \mathbf{T}_{\mathbf{grating.}}\ (1 - \mathbf{R}_{\mathbf{organic\ layers}}\mathbf{R}_{\mathbf{grating}})^{-1}\mathbf{E} \end{aligned}$$

The final field can be found by integrating over all plane waves.

3. SIMULATION RESULTS

cathode	**: 150 nm, n = 1.031 – 6.861j**
AlQ3	**: 30 nm, n = 1.655**
α-NPD	**: 30 nm, n = 1.807**
ITO	**: 120 nm, n = 1.806-0.012j**
SiON	**: 100 nm, n = 1.622**
glass	**: n = 1.528**

Figure 3. Organic layer stack.

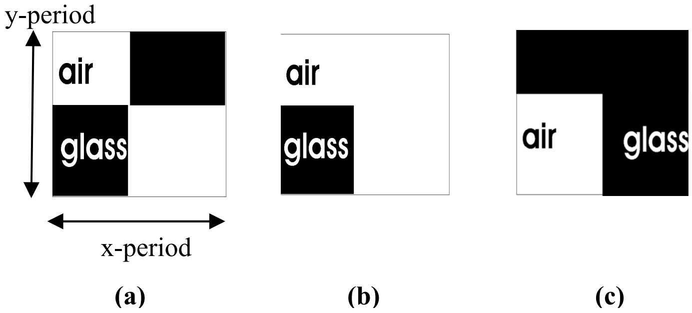


Figure 4. Top view of one period of the grating.

The used OLED layer stack is shown in Figure 3. This stack has been used to calculate for both emission and reflection of the organic layers. In the following discussion we make a distinction between the 3 grating types of Figure 4. In this figure we only show one period of the grating. We have investigated the influence of following parameters: period, filling factor and grating depth. For Figure 4 (a) and (b) we define the fill factor as the proportion between glass and period. The fill factor of Figure 4 (c) has been defined as the proportion between air and period. Although both the period and the filling factor can be varied independently in x and y direction, we always have used the same value in x and y direction. Unless indicated otherwise the used grating has a depth of 500 nm, a filling factor of 0.65 and a period of 1.0 µm.
We have found that a grating increases efficiency with approximately 50% compared to a planar interface. This is comparable with micro lenses. The distinction between 3 grating types only has implications for the determination of the optimal fraction.

3.1 Period

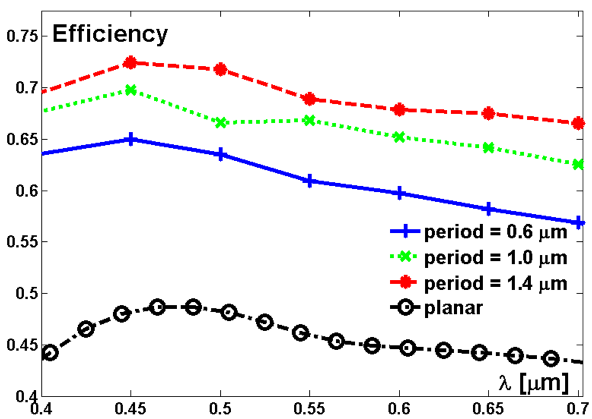


Figure 5. Efficiency in function of the wavelength for several grating Periods.

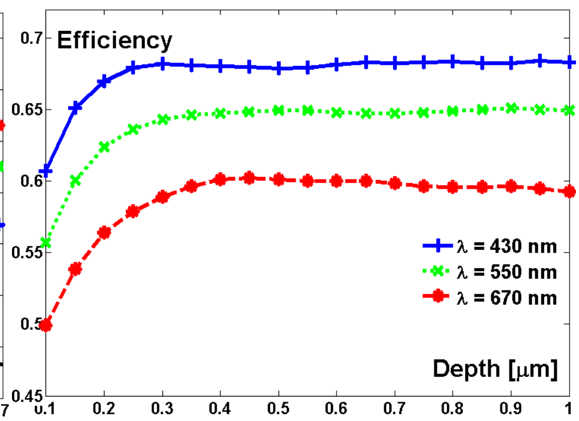


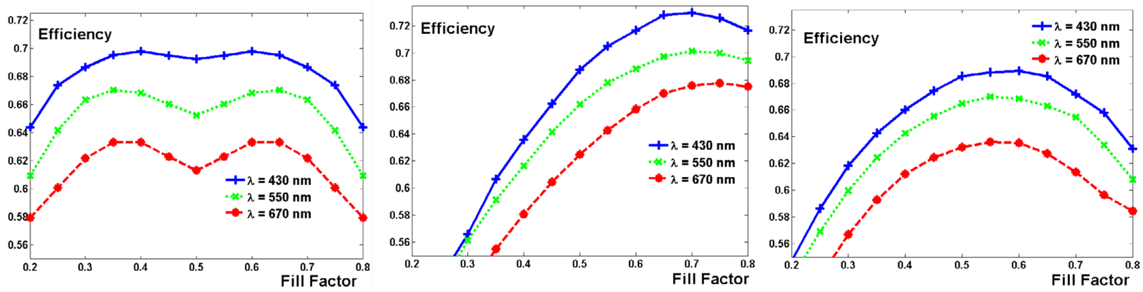
Figure 6. Efficiency in function of the Depth.

Figure 5 gives an indication of the efficiency boost achieved by using a grating based on Figure 4 (a). Using a planar interface at the glass-air interface we have calculated that approximately 45 % of the light is extracted to air. Using a grating on top of the glass, we see an efficiency of approximately 70%. Figure 5 shows an increase of efficiency for larger periods. This improvement for larger periods stops for periods larger than 1.5 µs. It should be noted that similar results were achieved by using grating types from figure Figure 4 (b) and (c).

3.2 Depth

Figure 6 shows the increase for efficiency for several wavelengths. A maximum efficiency is achieved for each wavelength. Longer wavelengths require more deep gratings. Taking into account the maximum wavelength of the visible spectrum a depth of 500 nm should be sufficient to maximize out coupling.
Similar results were achieved by using grating types from figure Figure 4 (b) and (c).

3.3 Fill factor



(a) **(b)** **(c)**

Figure 7. Efficiency in function of fill factor for several wavelengths. Each graph (a,b or c) corresponds with the grating type described in Figure 4.

Figure 7 shows the influence of the fill factor on the different grating types of ***Figure 4***. Each structure type has its own optimum. For a certain structure type, the optimal filling factor is the same for all wavelengths.

4. CONCLUSIONS

We have developed a simulation tool for gratings at the glass air interface for a bottom emitting OLED. Several parameters for different gratings have been investigated. A minimal depth is required for optimal efficiency. The efficiency increases for larger grating periods. This efficiency increase stops for grating periods bigger than 1.5 µm. We get an increase of 50% for the extraction efficiency compared to a planar structure. This is comparable with micro lenses. Future numerical simulation should give insight in the angular distribution of the emitted field. We plan to fabricate these gratings with interference lithography.

ACKNOWLEDGEMENTS

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