Improved Light Extraction Efficiency of Organic Light Emitting Diode using Photonic Crystals

Chaya B. M., Venkatesha M., Ananya N. and Narayan K.
Department of Electronics and Communication Engineering, Sai Vidya Institute of Technology, Rajanukunte, Bangalore, India

Keywords: Organic Light Emitting Diode, Photonic Crystals, Light Extraction Efficiency.

Abstract: In this work modelling of two dimensional of a fluorescence based Organic Light Emitting Diode (OLED) using plastic as flexible substrate is presented. The Finite Difference Time Domain (FDTD) mathematical modelling has been used to analyse the light extraction efficiency from fluorescence based Organic Light Emitting Diode (OLED). The OLED structure has been simulated by using 2D Hexagonal photonic crystal lattice. The Finite Difference Time Domain (FDTD) method is used to model and simulate the OLED structure. An enhancement of Internal Quantum Efficiency (IQE) and Light Extraction Efficiency (LEE) has been achieved by inserting Photonic Crystal above the emissive layer. The improvement in the extraction efficiency of OLED structure is achieved by increasing the radiative decay rate and by optimizing the angular distribution of light through the substrate.

1 INTRODUCTION

Organic Light Emitting Diode is an electroluminescence device which is formed using double layer structure of organic layers to produce light emission. This is achieved by driving voltage as dc source below 10 Volts (Tang and VanSlyke, 1987). If the radiative decay is high due to singlet exciton, then the process is said to be Fluorescence. In order to improve the extraction efficiency, the Photonic crystals is used upon the glass substrate to realize low power consumption using Nano imprint lithography technique which showed better performance than conventional OLEDs (Lee et al., 2003).

The state-of-art OLED stack is reviewed to determine radiative quantum efficiency and device efficiency during electrical operation which showed the significant results by varying electron transport layer. The efficiency is increased by incorporating various carrier transport layers in the OLED with different work functions (Do et al., 2003). The Silicon Nitride Photonic Crystals (PC) are used to control light which is acting as a dielectric medium to extract maximum amount of photons which is trapped in high index guided structures .

However different experiments on Organic LEDs are carried out using different structures of the Photonic crystals, substrates and the materials of the substrate may affect the thermal resistance (Kim et al., 2004). In this paper Poly (ethylene terephthalate) (PET) is used as a Plastic Substrate. PET has greater flexibility, robustness and is less expensive compared to glass substrate. The PET is a polymer electrode with high transmission in visible range of about 87% (Faraj et al., 2011).

Propitious research work is being carried out aiming at increasing the light extraction efficiency of OLED. In this paper an OLED with photonic crystals using plastic as flexible substrate with a point dipole source to increase the number of excitons in the emissive layer has been presented.

2 OLED STRUCTURE

2.1 Proposed Design

Figure 1, shows the structure of two dimensional OLED which is modelled using Lumerical FDTD (Finite Difference Time Domain). The proposed structure uses plastic as a flexible substrate. The modelled device structure consists of thin active organic layers which are integrated with the transport layers. The radiative recombination of injected electrons and holes is taken place in the organic layers. These transport and organic Layers

B. M. C., M. V., N. A. and K. N.
Improved Light Extraction Efficiency of Organic Light Emitting Diode using Photonic Crystals.
DOI: 10.5220/0006153902560259
In *Proceedings of the 5th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2017)*, pages 256-259
ISBN: 978-989-758-223-3

which is about 200nm is placed between anode and cathode layer placed on a plastic substrate.

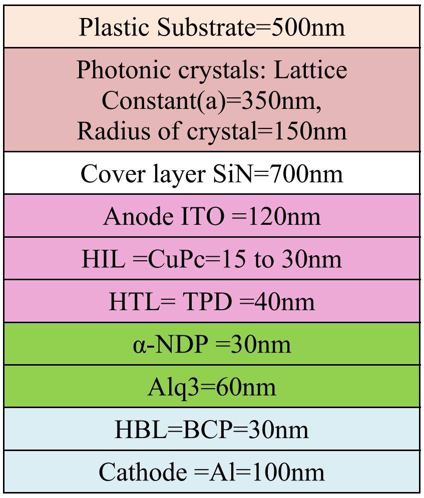

Figure 1: Fluorescence based OLED.

This device has been simulated using materials described in Table 1, green light is simulated having a peak wavelength of 540nm.

2.2 Modelling of Photonic Crystals in OLED

Figure 2, shows the modelled Photonic Crystal (PC), used in OLED. The PC used in this work has lattice constant of 350nm and radius is of 150nm. The simulation is done using Photonic crystal made up of Silicon Nitride which has refractive index of 1.9.

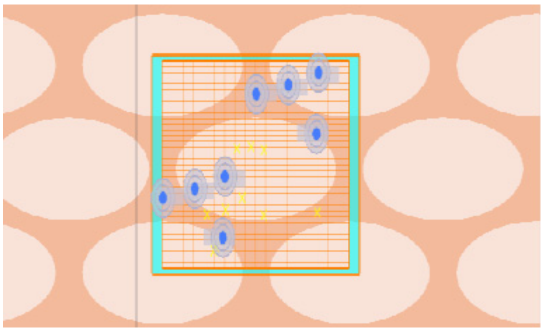

Figure 2: Modelled Photonic crystal Structure.

The Brillouin zone chosen is in the form of a hexagon as shown in Figure 2, Hence it is called as Hexagonal Lattice Brilloin Zone (Joannopoulos et al., 2008). The photonic crystals are placed in order to achieve better light confinement into the substrate without undergoing Total Internal Reflection as discussed in (Boroditsky, M et al., 1998).

3 OLED MATERIALS

The samples used in the structure are described in Table 1. The materials are chosen depending on the energy levels at metal organic interface abiding by Mott Schottky limit. The work function of electrodes, thickness variations and Organic Layers with the HOMO (Highest Occupied Molecular Orbital) and LUMO (Lowest Unoccupied Molecular Orbital) levels of organic molecules are given.

Table 1: Materials used in the OLED Structure.

Materials	Work Function	Refractive index(n)
Indium Tin Oxide	4.7eV	1.806
Aluminium	4.1eV	1.031
Hole Blocking Layer (HBL)-BCP	3.2eV	1.686
Hole Injection layer(HIL)-CuPC	3.1eV	0.47
Hole Transport layer(HTL)-TPD	2.6eV	1.67
Alq_3-Tris(8-hydroxyquinoline) aluminium	HOMO-5.62eV LUMO- 2.85eV	1.68
α-NDP- N,N`-diphenyl-benzidine	2.5eV	1.82
Cover layer –SiN	----	1.9
Substrate-Plastic	----	1.53

The most commonly used HIL is CuPC (Copper (II) phthalocyanine) is used to improve the carrier injection efficiency. The HTL used here is TPD (N, N'-Bis (3-methylphenyl)-N, N'-diphenylbenzidine). The hole transport layer and hole injection layer placed above organic layers. The hole injection layer is used to improve the carrier injection efficiency, and serves two purposes, first, it provides a path for smooth travel of injected holes up to emitting layer. Second, it functions like electron blocker to confine electrons within an emitting layer. The HBL used is BCP (2, 9 Dimethyl-4, 7-diphenyl-1, 10 phenanthroline with a work function 3.2eV. The organic layers used in the structure are α-NPD (N, N'-Di [1-napthyl)-N, N'-diphenyl-(1, 1'-bipheny)-4, 4'diamine) and Alq3- (Tris-(8-hydroxyquinoline) aluminium). The effective double injection is possible when the work function of metal electrodes is close to Lowest Unoccupied Molecular Orbital (LUMO) and Highest Occupied Molecular Orbital (HOMO) for Organic materials (Narayan et al., 2013).

4 METHODOLOGY

The Finite difference Time Domain (FDTD) method is used for solving Maxwell's equations in complex geometries. The Maxwell's equations are time dependent hence, FDTD simulations has high performance optical solver which can capture using wavelength scale structure to improve the device. In order to achieve the maximum radiative decay, the derivation is published in (Novotny and Hecht ,2006), where the quantum radiative decay is proportional to classical dipole power radiated, the relationship as in equation (1)

$$\Gamma_{decay} = \mathrm{P}_{rad} \tag{1}$$

This relation is shown to relate the radiative decay rate to Fermi's golden rule about the density of photonic modes which is represented in equation 2, as represented in (Joannopoulos et al., 2008),

$$\Gamma_{ij} \alpha |M|_{ij}^{2} \rho(v_{ij}) \tag{2}$$

where Γ_{ij} = transition rate from higher energy state i to lower energy state j, M_{ij} related to wave function overlap of excited states, $\rho(v_{ij})$ is photonic mode density of transition.

In this work two results have been interpreted, Internal Quantum Efficiency (IQE) and Light Extraction Efficiency (LEE) (Chutinan et al., 2005).

The Internal Quantum efficiency is the radiative decay process achieved by relating decay rate to the power radiated by the single dipole source. With the dipole source implementation, we can formulate IQE. From, Fermi's Golden rule, we can relate decay rate to density of states and is related to Classical EM power emitted by a dipole to imaginary part of green's function (Novotny and Hecht ,2006).

The decay rate enhancement is given by,

$$\frac{\gamma_{decay}}{\gamma_{decay}^{0}} = \frac{\text{dipole power}}{\text{source power}} \tag{3}$$

The Light Extraction Efficiency (LEE) is defined as the fraction of optical power generated in the active layer of the OLED that escapes into the air above the OLED within a desired range of angles.

$$LEE = \frac{\gamma_{rad}}{\gamma_{rad} + \gamma_{loss}} = \frac{LEE_{pattern}}{LEE_{no\_pattern}} \tag{4}$$

where, γ_{rad} =Electro Magnetic decay to Far-field radiation, γ_{loss} = EM decay trapped by Total Internal Reflection

The light escaping to the glass substrate within a particular solid angle (e.g. bounded by the TIR critical angle) is considered. Therefore, the total extraction efficiency (TEE) is given by, combination of internal quantum efficiency (IQE) and Light extraction efficiency (LEE).

$$TEE = IQE \times LEE \tag{5}$$

5 RESULTS

5.1 Extraction Efficiency Analysis

For the proposed OLED structure, the far field into air with Photonic crystals (PC) patterning and without PC patterning is simulated. The Improvement in the light extraction within bounded critical angle for a wavelength of 540nm is observed in Figure 3.

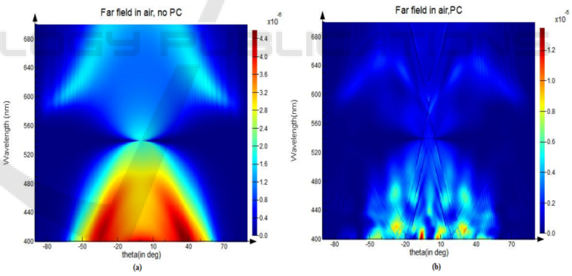

Figure 3: Light extraction efficiency (far-field in air, with and without PC.

5.2 Angular Distribution of Light at 540nm

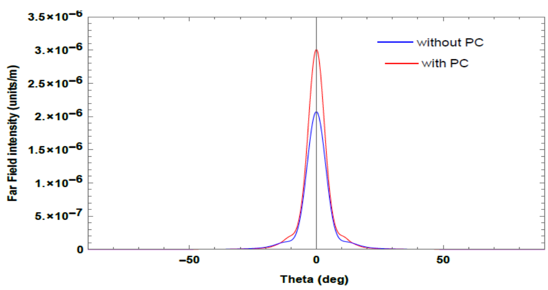

Figure 4: Angular Distribution of light.

Figure 4, shows the Far field intensity observed for the bounded critical angle of about 3.2 µm Volts/m with the presence of photonic crystal in the OLED structure and 2.1µm Volts/m for structure without Photonic crystal at a wavelength of 540nm. The proposed model having photonic crystals inserted above the emissive layer, if implemented in the organic light emitting diode will improve the light extraction efficiency.

5.3 Internal Quantum Efficiency

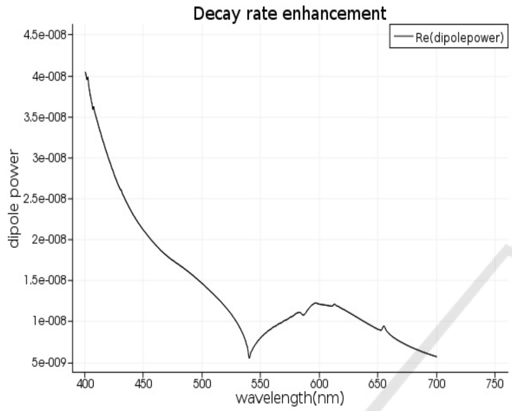

Figure 5: Dipole power versus Wavelength.

Figure 5 shows a plot between dipole power versus wavelength. It can be seen from figure 5, that dipole power is highly dependent. The exponential decay in the figure 5 indicates that the maximum decay occurs when the wavelength is 540nm. This implies that there is an increase in number of excitons produced at this wavelength. The dipole power consumed at this wavelength is 5.71e-009 Watt.

6 CONCLUSIONS

In this work Finite Difference Time Domain (FDTD) modelling of an fluorescence based OLED using plastic as flexible substrate has been presented. A high radiative decay rate has been achieved at 540 nm by inserting a photonic crystal above the emissive layer. A high decay rate not only enhances the internal Quantum efficiency but also light extraction efficiency, it has been shown that an Green emitting OLED on the plastic substrate has maximum internal quantum efficiency and light extraction efficiency at an wavelength of 540 nm. We have shown that Green emitting OLED on plastic substrate has maximum Light Extraction efficiency of 3.2 µm Volts/meter at a wavelength of 540 nm using the photonic crystals at 550THz. Fabrication of such OLED structures can find future application as a monolithically integrated light source for integrated optical Lab-on-a-Chip based bio-sensors.

ACKNOWLEDGEMENTS

The authors would like to thank Science and Engineering Research Board, Department of Science and Technology (DST-SERB) Government of India for funding this research work. File No. YSS/2015/000382

REFERENCES

Tang, C. and VanSlyke, S. 1987. Organic electroluminescent diodes. *Applied Physics Letters, 51 (12), p.913.*

Lee, Y., Kim, S., Huh, J., Kim, G., Lee, Y., Cho, S., Kim, Y. and Do, Y. 2003. A high- extraction-efficiency Nano patterned organic light-emitting diode, *Applied Physics Letters, 82(21), p.3779.*

Do, Y., Kim, Y., Song, Y., Cho, C., Jeon, H., Lee, Y., Kim, S. and Lee, Y. 2003. Enhanced light Extraction from Organic Light Emitting Diodes with 2D SiO2/SiNx Photonic Crystals. *Advanced Materials, 15 (14), pp. 1214-1218.*

Kim, Y., Song, Y., Y. W., & Lee, Y. H. 2004. Enhanced light extraction efficiency from organic light emitting diodes by insertion of a two-dimensional photonic crystal structure. *Journal of Applied Physics. 96(12), 7629.*

Faraj, M. G., Ibrahim, K., Ali, M. K. M. 2011. *PET as a plastic substrate for the flexible optoelectronic applications, Optoelectronics and Advanced Materials–Rapid Communications. 5(8)*

Boroditsky, M., Coccio1i, R., Yablonovitch, Eli. 1998. Analysis of photonic crystals for light emitting diodes using the finite difference time domain technique, *SPIE, Vol. 3283.*

Novotny, L. and Hecht, B. 2006. Principles of Nano-Optics, *Cambridge, Cambridge University Press.*

Chutinan, A. et al., 2005. Theoretical Analysis on light-extraction efficiency of organic light-emitting diodes using FDTD and mode expansion methods, *Organic Electronics. 6(1), pp.3-9.*

Joannopoulos, J., Johnson, S., Winn, J. and Meade, R. 2008. Photonic Crystals, Molding the Flow of Light. *2nd ed. Princeton: Princeton University Press.*

Narayan, K., Mohan Rao, G., Varadharajaperumal, S., Manoj Varma, M and Srinivas, T. 2013. Effect of thickness variation of hole injection and hole blocking layers on the performance of fluorescent green organic light emitting diodes, *Current Applied Physics 13(1), pp.18-25.*