Directional Light Extraction Efficiency Enhancement of LED Using Nanostructure 1D Triangular GaN Grating on the Top

R. Ghosh[1*], K.K. Ghosh[1] and R. Chakraborty[2]

[1] Department of Physics, Institute of Engineering & Management
Salt Lake, Kolkata, INDIA
[2] Department of Applied Optics & Photonics,
University of Calcutta,
92 A.P.C. Road, Kolkata-700 009, INDIA
*Email: rajibghosh77@rediffmail.com

***Abstract*—Improvement of the front directional light extraction efficiency of Light Emitting Diode (LED) has been analyzed using nanostructure one dimensional triangular grating. The III-V GaN and intermediate air gaps form the grating system in this present study. Distribution of the magnetic field and the outgoing flux has been analyzed using Finite Difference Time Domain (FDTD) method. Coupling of light modes from the LED structure with the nanostructure triangular grating enhances the light output power of the entire structure.**

Keywords-1d triangular grating; enhancing extaction efficiency; FDTD method; Field Distribution; Nanostructure; Quantum Efficiency; MEEP.

I. INTRODUCTION

Light emitting diodes (LED) are being widely used in modern days because of its energy saving and environment friendly nature. The optical performance of LEDs is comparable to the luminosity of florescence light source. The LEDs are used in solid state lighting, in liquid crystal displays, in different colored illumination panels, traffic signals etc. But the light output efficiency of the conventional LEDs is very poor. This is because of two reasons viz. total internal reflection at the interface of active layer with surroundings and progressive absorption of the propagating light originated in the active layer. In modern days the internal quantum efficiency of the LEDs has been improved up to or little beyond 90% by the development of the epitaxial growth and device fabrication technology[1]. However the light extraction efficiency (LEE) of conventional LEDs are nearly 20% or little beyond[2]. A number of research papers have been published suggesting ways to improve the LEE or the external quantum efficiency in LEDs. Surface Roughening [3-5], Photonic Crystals [6-11], Nanopyramids[12], Surface Plasmons[13,14], Surface grating [15] etc. are some of the interesting approaches. Interesting reports [18] are also made on improving the efficiency by using top transmission grating only. For the improvement of LEE of conventional LEDs, optical design of nanostructure triangular one dimensional GaN grating has been placed on the top of the LED structure. The Finite Difference Time Domain (FDTD) method has been utilized as an efficient tool for this. Using FDTD in 'MEEP' simulator the electromagnetic field distribution inside and outside the LED structure has been analyzed. Outgoing Flux calculation using a Gaussian source with and without the grating structure on LED is under investigation. This paper has been organized by giving theory and FDTD simulation in section (II). The results and discussion is given in section (III). The section (IV) is the concluding section.

II. THEORY

A. Extraction Efficiency

For the detection of external quantum efficiency' (η_{Q-ext}) [19] can be represented as

$$\eta_{Q-ext} = \frac{\text{Detected output Photons}}{\text{Injected electron-hole pair}} = \eta_{\text{int}}\,\eta_{extr}\eta_{cap} \tag{1}$$

where 'η_{int}' is the 'Internal Quantum Efficiency' .Which indicates the fraction of photons generated inside LED per electron-hole pair injected. 'η_{extr}' is the 'Light Extraction Efficiency'(LEE). LEE defines fraction of photons generated inside LED which escaped. 'η_{cap}' is the ' Detector Capture Efficiency' . Capture efficiency is the ratio of detected photons per escaped photon.

The 'external quantum efficiency η_{ext} can be represented as

$$\eta_{ext} = \eta_{inj}\eta_{\text{int}}\eta_{extr} \tag{2}$$

where $\eta_{inj}, \eta_{\text{int}}$ and η_{extr} are 'Injection Efficiency', 'Internal Quantum Efficiency' and 'LEE' respectively. Internal

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quantum efficiency is the ratio of radiative recombination rate to the total recombination rate.

The fractional enhancement of efficiency or power or outgoing flux by using grating structure on LED is

$$F = \frac{\eta_{ext}\,(\text{With Grating})}{\eta_{ext}\,(\text{Without Grating})} \quad (3)$$

B. Mode-Coupling

Imposing boundary conditions on Maxwell equations, from the coupled mode theory [16,17] we get

$$< \mathbf{H}_{Grating}, \boldsymbol{H}_L > \; = \int_{interface} \overset{*}{\boldsymbol{H}}_{Grating}(\boldsymbol{r}).\boldsymbol{H}_L(\boldsymbol{r})dA \quad (4)$$

where '*' denote the complex conjugate. $H_{Grating}$ and H_L are the scalar magnetic mode field in the triangular grating and bulk LED respectively. Using plane wave solution, we can write

$\boldsymbol{H}_L = \boldsymbol{H}_0 e^{j\vec{k}.\vec{r}}$ and

$$\boldsymbol{H}_{Grating} = e^{j\vec{k}_B.\vec{r}} \sum_{m_1}\sum_{m_2}\sum_{m_3} \vec{u}_{KB}(m_1, m_2, m_3) e^{j(m_1\vec{b}_1 + m_2\vec{b}_2 + m_3\vec{b}_3).\vec{r}} \quad (5)$$

where

$\vec{k}$ = wave vector, $\vec{u}_{KB}$ =Fourier constant of u_{KB}, $\boldsymbol{K}_B$ =Bloch wave vector, m_i = summing indices, $\vec{b}_i$ =Primitive reciprocal lattice vectors.

In Fig.1 an one dimensional triangular grating is placed on the top of the homogenous LED material having dielectric constant ε_L is shown. At the x-y interface plane of grating and LED where along x-direction the primitive reciprocal lattice vector $\vec{b}_1$ is present.

$$< \boldsymbol{H}_{Grating}, \boldsymbol{H}_L > = \sum_{m_1} \vec{u}_{KB}(m_1) e^{K_z Z} \int_{x=-\infty}^{\infty} e^{j(K_{xy} - K_B - m_1\vec{b}_1).\vec{r}} .dx \quad (6)$$

C. FDTD Simulation Model

In this simulation, a Gaussian source has been placed in the middle of p-GaN layer. The outgoing flux calculation has been done by using Finite Difference Time Domain (FDTD) analysis using Maxwell's equations. Perfectly Matched Layer (PML) has been placed outside the total structure. To set the transmitted power at a given frequency 'ω', Poynting vector $P(\omega)$ along normal $\hat{n}$ direction can be written as

$$P(\omega) = \mathrm{Re}\,\hat{n}.\int \vec{E}_\omega(x) \times \vec{H}_\omega(x) d^2x \quad (7)$$

Using Gaussian pulse Fourier Transform of $\vec{E}_\omega(x)$ and $\vec{H}_\omega(x)$ for every point in the flux plane has taken using summation over 'n' time steps.

III. Results and Discussion

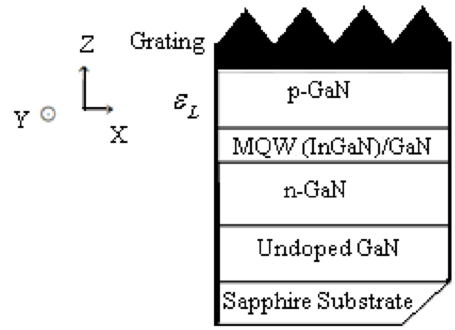

Fig.1 Triangular grating structure is placed above the LED having dielectric constant of p-GAN layer is ε_L

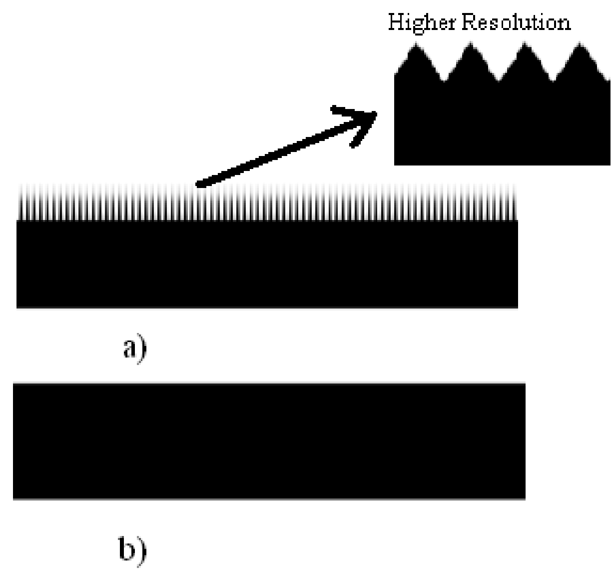

Fig.2 Triangular 1D grating on bulk LED (a) and bulk LED Without grating (b). Higher resolution of triangular grating shown on top.

On the top of the LED structure one dimensional nanostructure triangular grating has used as shown in Fig.1 for the enhancement of the light output from LED. Fig.2 shows the top portion of the LED with and without triangular grating. Lattice constant of the 1D triangular grating has taken about 400 nm. Fig. 3 shows the distribution of the magnetic field surrounding the LED with and without triangular grating on the top. It is clearly seen in Fig. 3 after using nanostructure triangular grating on the top of LED the magnetic flux distribution is much more concentrated in forward direction than without using any grating. MEEP FDTD simulation has been used for that. In MEEP simulation output flux spectrum is considered as a ratio of transmitted to the incident

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intensities of the Gaussian source. Frequency of the Gaussian source is set in the visible spectrum region.

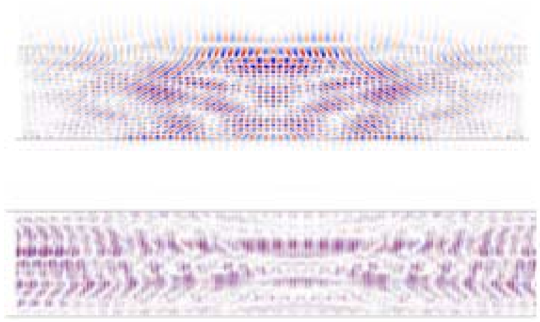

Fig.3 Front directional outgoing Flux (Magnetic Field) distribution with triangular grating (top) without any grating (bottom).

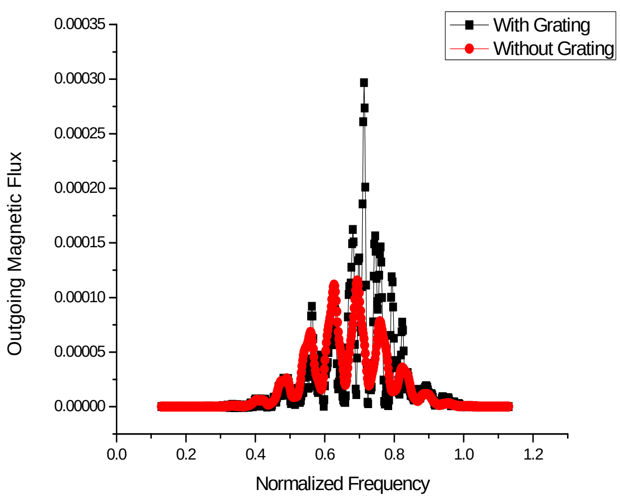

Fig.4 Flux output in front direction with triangular grating (green) and without grating (red).

The simulation has been done by using GaN(d.e.c=5.3)/air periodic system as grating structure.

Simulation result in Fig.4 shows that the output light flux is maximum when GaN-air materials are used in nanostructure grating and minimum when no grating material is used on the LED top. Results in Fig.4 shows that the LEE enhances by using nanostructure triangular grating on LED top.

IV. CONCLUSION

Enhancement of extracted light from LED using nanostructure PC has realized by FDTD simulation. Within different III-Nitride materials GaN and air are chosen for the two materials of binary nanostructure triangular grating on the LED top.

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