

# Improvement of Quality Specifications of Light-Emitting Diodes based on the Photonic Crystals

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**Abstract** – In this paper, a new structure of Light-Emitting Diodes (LEDs) based on the usage of Gallium Nitride (GaN) semiconductors has been proposed in which, in order to improve the efficiency of the output light, a reflective layer along with two Photonic Crystal (PC) layers have been employed. The applied changes and their optimization illustrated increase in output light efficiency as much as 133% with respect to a typical LED.

**Keywords:** LED, Photonic Crystal, GaN, Finite-Difference Time Domain (FDTD)

## 1. Introduction

Light-Emitting Diode (LEDs) are members of semiconductors which emit photons when current goes through them in the permissible direction. They can produce lights such as visible, ultraviolet and infrared depending upon the matters used within them. In a world where the natural energy resources are going to be finished, optimal utilization of available energy resources is one among most important issues. The LEDs have low powers and long life devices. They are, thus, attracted wide attentions which have led to their mass productions. An LED has low external quantum efficiency (approximately 4%) despite nearly 100% one in the internal quantum efficiency; this is a consequence of the total reflection phenomenon [1]. Due to widespread applications, low prices and long lifetime, there is a necessity to pursue solutions to increase their output powers. As a result in this effort, various methods have been proposed such as changing the structure [2], recreation of photons [3], increasing the external surface [4], usage of the reflective layer [5] and employing ITO layers on their external surfaces [6]. Also, the Photonic Crystals (PCs), recently, have attracted much attentions. Among these methods, the two firsts are not worthy enough due to their low efficiencies, higher costs and manufacturing problems. The external surface increases is also in company with random reflections and destruction of light emissions. Lately,

however, using PCs technology in LED manufacturing has given rise to hopeful results regarding improvements in emitted light its direction [7-10].

In this paper, in order for analysis and calculation of the LEDs' output power, the Finite Difference Time Domain (FDTD) has been used. The structure of the paper is as follows. In the next section, the limiting factors of LEDs' efficiencies and role played by the PCs to solve these issues will be discussed. In section 3, designs and optimizations of LED manufacturing are presented and finally, the last section considered for the concluding remarks.

## 2. Limiting Factors of LEDs Output Power

As it was mentioned before, extraction of photons produced in the active section of LED faces intensive problems. Among the factors effective on this issue is wrong unsuitable orientation of direction of generated photons emission as well as the total reflection phenomenon.

Photons which emitted not in the emission light direction out of LED must be able to leave the semiconductors in the shortest possible time. If not leaving the semiconductor due continuous reflection off other surfaces, they would be destroyed through the absorption process and would not be able to help to increase the output power efficiency. With placing a reflective layer usually made up of silver, parts of photons emitted downwards will reflect off of the silver layer upon incident and will be transmitted to the external layer; among these, photons with angular direction less than the critical angle can leave the structure and thus, play role in increasing the output power efficiency. The PCs on the other hand, using the improvement in the direction of emission will significantly help to lowering the leaving time of photons [11].

The most important limiting factor of LEDs' efficiency

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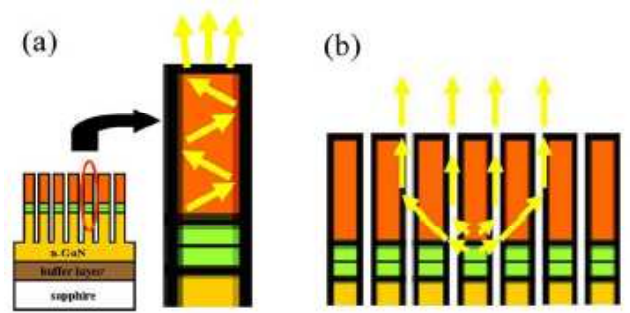
is the total reflection phenomenon [12]. According to the Snell law, when light passes from a higher density environment to a lower density one, conditioned on the incident angle be lower than the critical angle, it can enter the new environment; otherwise, it will reflect off the boundary between two environments totally. Based on the law of power conservation, Snell's law and Lambertian emission pattern, power of light leaving the surface of a planar semiconductor and entering the second environment is calculated by,

$$\eta_{external} = \frac{P_x}{P_s} = \frac{1 n_x^2}{4 n_s^2} \quad (1)$$

In which  $n_s$  and  $P_s$  denote, respectively, the refractive index and output light power of the first environment and  $n_x$  and  $P_x$ , those of the second environment. According this relationship, the efficiency of the light emitted of GaN into the air equals 4%. When benefiting from the ITO on the external surface of GaN, since its refractive index differs from that of the GaN ( $n_{ITO}=2.1$ ), using (1), the efficiency reaches as much as 17%.

### 2.1. Role of PC on Enhancement of LED's Features

PCs are devices whose electrical constant, spatially, change periodically in specific directions. They increase the efficiency of light's output power through two mechanism. First, each nanometer of PC behaves like a cylindrical tube for wave conductance. The photons generated within the LED are divided into two categories: permissible and impermissible. The class in which modes distribution of nanotubes are belonged to, as in Fig. 1a, using the perpetual reflection off the internal surface and creating internal interference between the permissible modes, have vertical wave emission direction; thus, they are led into out of the structure (waveguide property). The other class which is not belonged to the permissible distributed mode nanotubes while the generated photons having passed their corresponding nanotubes, deviates into vertical direction based on the Snell law, then simply become members of the next permissible distributed modes of nanotubes and using the process just like explained, their fields are oriented vertically; thus, they could be also escape from the structure (Bragging property) [14]. This process is illustrated in Fig. 1b.



**Fig 1:** (a) The mechanisms of permissible leaving modes from the PC nanotubes, (b) passage of impermissible modes of nanotubes and becoming part the next permissible nanotube modes and leaving the structure.

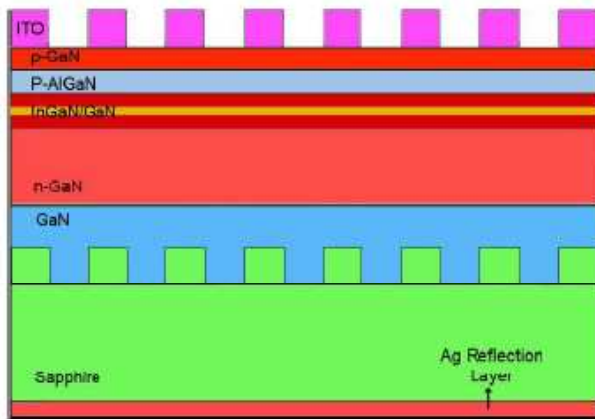
## 3. Design and Optimization of LED Structure

### 3.1. Simulation Software and its Configurations

In this paper, the FDTD has been used for analysis and computation of the output power of light. The method provides solving the Maxwell equations with conversion of the area into tiny section and creation of a mesh network along with simultaneous analysis of electric and magnetic fields [15]. In order to save hardware resources implementing the simulation, depending on the used materials, the dimensions of the finite sections ( $\delta$ ) can be set to largest possible values which preserve the accuracy of the solutions. For all the applied simulation scenarios, a light Gaussian source field has been employed within the Multiquantum Well (MQW). As for general configuration of the simulation parameters, the wavelength of the light source has been considered to be 460 nm, which corresponds to the light emitted from GaN semiconductors and that of the blue colors. Also, for the boundaries of the simulation area, the Perfectly Matched Layer (PML) is assumed to be 500 nm.

### 3.2. Proposed Method

The general structure of the proposed method is depicted in Fig. 2. In this structure, the lower layer is composed of silver, the lower PC grating (PC-G) of Sapphire and the higher PC-G from the ITO. In the given structure, also, the materials used for the MQW of the active area of LED are limited to combinations of InGaN and GaN. The thickness and refractive indices of layers have been given in Table I.



**Fig. 2:** The proposed LED structure

**Table I:** The thicknesses and refractive indices of the applied materials in the LED

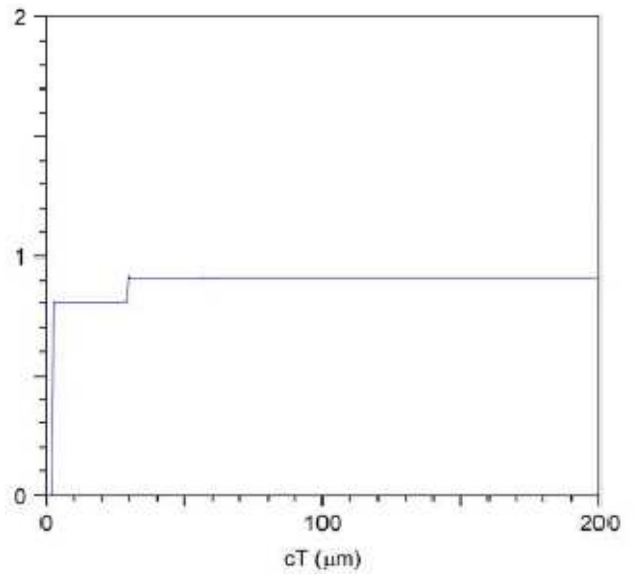
Material	Thickness	refractive indices
p-GaN	0.12	2.5
p-AlGaIn	0.05	2.5
INGaIn/GaN	0.115	2.6
MQW		
n-GaN	2	2.5
GaN	3	2.5
Sapphire	4	1.77
Ag	0.01	90%reflect

### 3.3. Simulation and Optimization

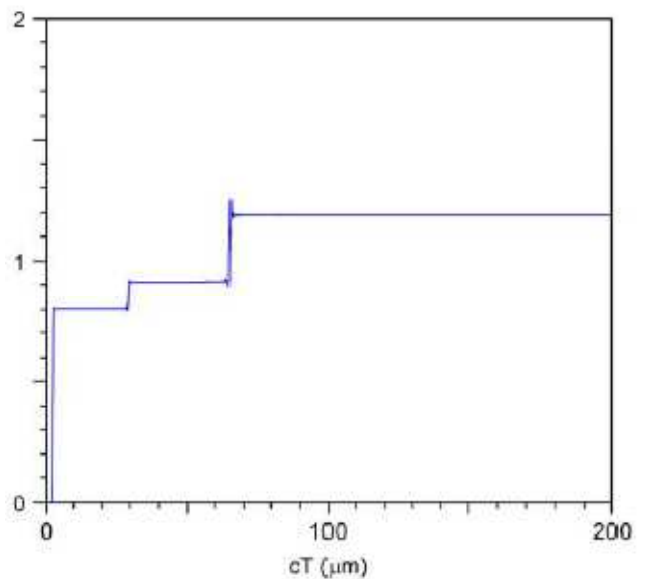
To design and optimization of the structure in Fig.2, first, the output power was calculated in the absence of PC-Gs and silver layer, which was equal to 3.64%. According to (1), the maximum output power of this structure without PC-G must be equal to 4%, showing goodness of the simulation conducted here.

To make the results more representative, all the values are multiplied by the constant number of  $k=25$ . This operation is adopted throughout the paper. Thus, the relative output power of the above LED would become 0.91. The Fig. 3 shows the relative output power assuming the above considerations.

In the next step, the silver layer was added to the low surface; this has led to 1.21 in the relative output power, i.e., 33% increase in the output power of LED; the Fig. 4 demonstrates the relative output power for this case.



**Fig. 3:** The output power of LED without presence of PC-G and silver layers.



**Fig. 4:** The output power of the LED with addition of the silver to lowest layer

Following the above procedure, a low values of PC-G was added to optimize the basic parameters, that is, lattice constant, tube height and the Filling factor (FF), which depicts the relative value of the width of PC-G with respect to the lattice constant; this case accordingly was simulated. Since parameters do not have any priority for the optimization purpose, here, arbitrarily, with following of the routines of the similar studies, firstly, the lattice constant and height are assumed as constant and with the typical values, and FF has been increased from 10% to 100%, with 10% difference from one step to the next one; the results output power are shown in Fig. 5, respectively. From the figure, when FF equals 70%, the output power of LED has its maximum.

In the next step, in order to find the optimal lattice constant, the optimal value of FF has been adopted. Fixing FF and height into constants, value of lattice constant is considered to be 100, 230, 460, 690, 920, 1130 and 1500, all in nm (some of these values are integer multiples of  $\lambda/2$ ). Fig. 6 shows optimal values of the output power versus different values of lattice constants. Pursuing this procedure, in the next step, height parameter is varied and taken values of 100, 230, 460, 920, 690, 1130 and 1500nm, for the purpose of optimization of a low PC-G in which the lattice constants are resumed to be at their optimal points; for each step, then the output power has been measured. Fig. 7 illustrates results of this simulation.

The results of the optimization over the basic parameters of a low PC-G are shown in Fig. 11; from the figure, it can be inferred that the efficiency of the output power of the LED can be increased, with respect to typical LED, to as much value as 114% using the reflective layer and PCs' specifications.

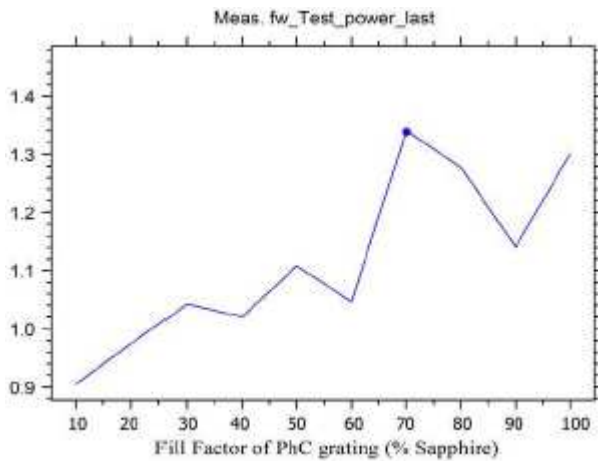


Fig. 5: Optimization of FF parameter for a low PC-G

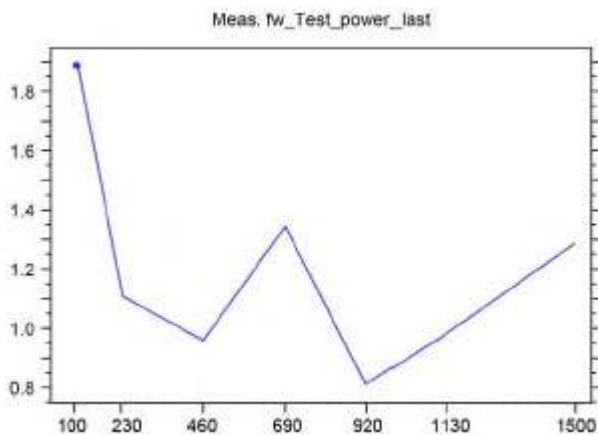


Fig. 6: Optimization of the lattice constant for a low PC-G

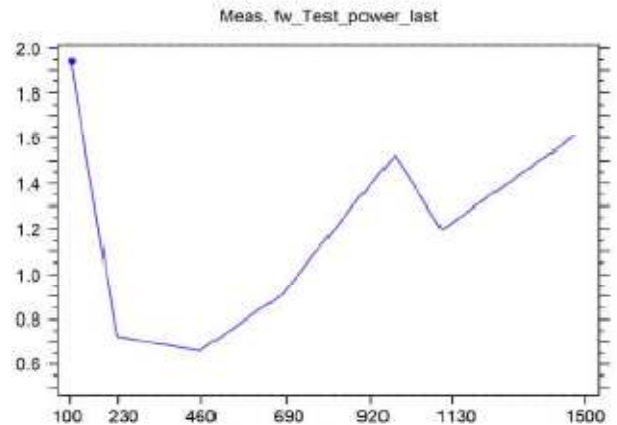


Fig. 7: Optimization of the height parameter for a low PC-G

The last simulations are dedicated to the role of addition of the PC-G with ITO layer on the upper surface of LED and computation of the optimal values of basic parameters, that is, FF, lattice constant and the height; the corresponding relative output powers are then recorded to find the optimal values. For this simulation and thus parameter optimization, as it has been done in the simulation of the previous section, out of the three parameters, two of them are kept fixed and the remaining one is varied to observed according effects. Keeping this way mind, first, lattice constant and height are fixed while FF has increase from 10% up to 100% with 10% steps. The result, as given in Fig. 8, has shown that the maximum output power is achieved for FF equal to 90%.

In the Fig. 9, the optimal output power for fixed FF and height and along with a variable lattice constant taking values equal to 100, 230, 460, 690, 920, 1130 and 1500 nm has been recorded. It can be seen that a lattice constant equal to 100 will give the maximum output power.

Finally, assuming the optimal values for FF and lattice constant, the PC-G height is changed as before, taken values 100, 230, 460, 690, 920, 1130, and 1500 nm. Fig. 10 shows that the optimal output power is realized for PC-G height equal to 690nm.

With the replacement of the analyzed parameters with optimal values, it can be observed that addition of an ITO PC-G to a structure including low PC-G and reflective layer, a relative output power efficiency of LED as much as 133% can be accessed as compared to a typical LED. Fig. 11 compares the relative output power efficiency of the LED versus the optimized parameters. The optimal results of the simulation as well as the improved percentages of the output powers are given in Table II.

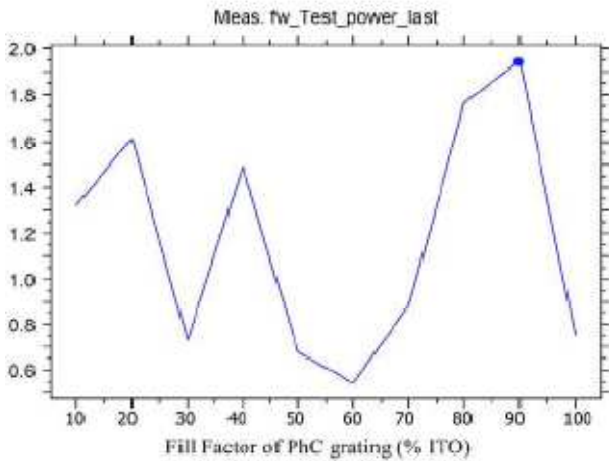


Fig. 8: Optimization of FF for high PC-G

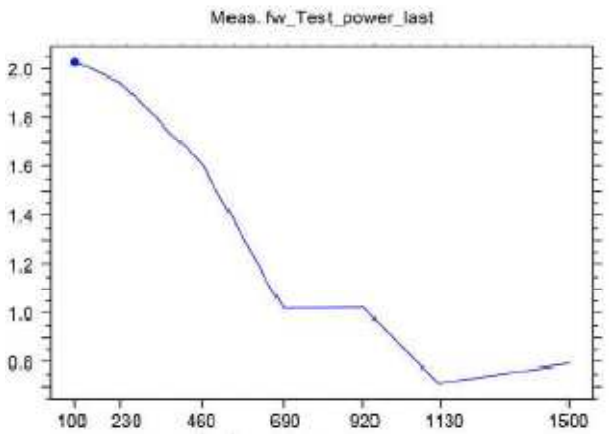


Fig. 9: Optimization of lattice constant for a high PC-G

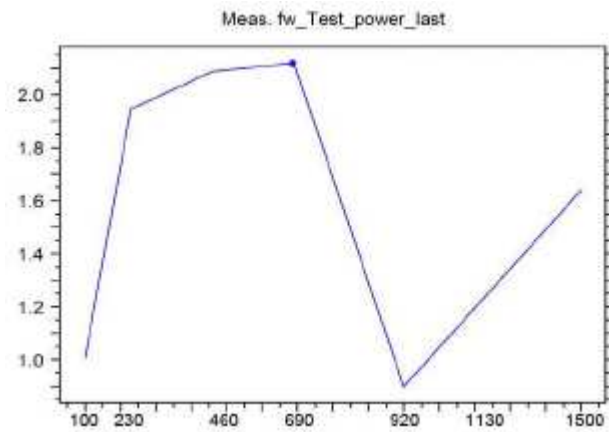


Fig. 10: Optimization of height for high PC-G

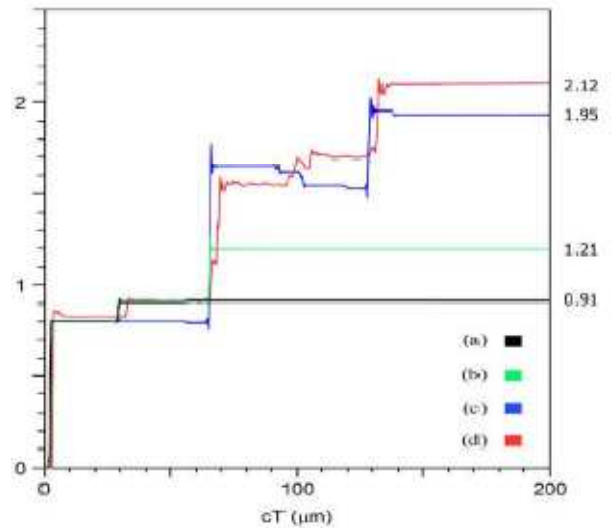


Fig. 11: The relative output power of LED: (a) typical, (b) covering the floor surface with silver, (c) silvered floor and low PC-G and (d) silvered floor for low and high PC-G

Table II: The simulation results for the proposed optimization design

	Ag	Low PhC-G		High PhC-G			
Parameter	-	FF(%)	Lattice cons.(nm)	H(nm)	FF(%)	Lattice cons.(nm)	H(nm)
Optimized parameter	-	70	100	100	90	100	690
Max output power	1.21	1.95		2.12			
Performance optimization	33 %	114%		133%			

### 4. Conclusions

In this study, the limiting factors of the output light power of LEDs have been introduced and solutions offered to overcome them. Following this, the operational behaviors of ITO, reflective layer and Photonic Crystals (PCs) have been studied for the purpose of overwhelming the limiting factors. Finally, simulations have been done to analyze the optimal performance of the proposed method based on the Gallium Nitride (GaN) semiconductors.

To this end, firstly, the output power of the LED was

computed in the absence of the above factors in order to build up a benchmark for further comparisons. It has been observed that addition of silver to the floor will increase output power up to 33%. Following this, an increase of PC-G made up of a similar matter as one in the sublayer of the lowest layer of the active area, optimizations have been done, respectively, for Filling-Factor (FF), lattice constant and height of the PC; the simulation suggested that with addition of PC whose parameters have been optimized, an increase in the relative output power equal to 114% in the lower surface layer of the structure can be achieved. Lastly, with covering the upper layer using ITO materials, inclusion of the silver layer and considering an improved low PC-G, the relative output power has experienced 133% increase when the basic parameters are optimized. Therefore, it has been shown that using the mentioned factors and based on the proposed structure, the efficiency of the output power can be improved from 3.64% for a typical LED to as much as 8.5% for the proposed one.

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