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Studies of the light output properties for a GaN based blue LED using an electro-optical simulation method

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ABSTRACT

In this study, an electro-optical simulation method is developed to predict the light intensity distribution and luminous flux of an in-house fabricated GaN based blue LED chip. The entire modeling process links an electrical simulation with ANSYS and optical simulation with LightTools, by assuming a proportional relation between the distributed current density and light emission energy on the multiple quantum well (MQW) layer. Experimental results show that the proposed simulation method can give a good prediction on the light intensity distribution for a semi-packaged GaN based blue LED chip. Further analysis on the simulation results reveals that an increase of at most 8% of the luminous flux can be achieved when the current density is controlled to evenly distribute on the MQW layer whereas the chip structure and electro pattern remains the same.

1. Introduction

In the design of a Light Emitting Diode (LED) chip structure, optimization of the current density on the Multiple Quantum Well (MQW) layer attracts a lot of attentions. The reasons are from two aspects [1–15]: firstly, a uniform current density distribution enables the uniform heat dissipation on the MQW layer, resulting in an effective thermal treatment on the LED chip. Also, it enables a uniform light emission on the MQW layer, resulting in a high Light Extraction Efficiency (LEE) of the LED chip. In general, improvement of the current density distribution on the MQW layer can be made by inserting a Current Block Layer (CBL) [3–6], Current Spreading Layer (CSL) [7–11] or both of them [8] into the LED chip. The CBL is usually made of SiO_2 and it is preferred to be laid in the p-electrodes for vertical LEDs, or under the p-electrodes for lateral LEDs [7,8]. The Indium Tin Oxide (ITO) has been considered as the most proper material to generate the CSL for a long time. However, several previous studies reveal that graphene exhibits a better behavior and has the potential to substitute the traditional ITO materials in future [7,11]. The CSL is laid above the p-GaN layer for both the vertical and lateral LEDs.

Another frequently used solution to improve the current density distribution on the MQW layer is the electrode optimization of the LED chips [12–15]. Hwang et al. developed a 3D circuit model to predict the light output power of lateral LEDs with certain electrode patterns [12]. Tu et al. experimentally and numerically investigated the light output power of a vertical LED with different pre-designed electrode pattern [13]. As reviewed, they developed a design approach for high luminous efficacy by optimizing the electrode pattern of the LED chip in a 3D numerical simulation model, and finally obtained an optimized electrode pattern that can enhance the light output power by 11%.

However, in most of the above-mentioned studies, the optimization of the electrode geometry is only conducted to get an even distribution of current density over the MQW layer. Actually, the effects of the electrode pattern on the light output properties of a LED chip are twofold. In addition to the strong impact on the current density distribution over the MQW layer, the electrode pattern also affects the LEE of the LED chip by obstructing the light rays emitted from the MQW layer out of the chip, known as the shadowing effect of the electrodes. For example, Chen et al. developed an electro-optical numerical simulation to reveal the effect of the resistivity of the CSL on the current crowding on the MQW layer in a lateral LED chip [10]. They claimed that a high LEE of the LED happened when the current was not uniformly distributed on the MQW layer but crowded near the n-contact electrode. This may attribute to the shadowing effect of the p-contact electrode lessens the

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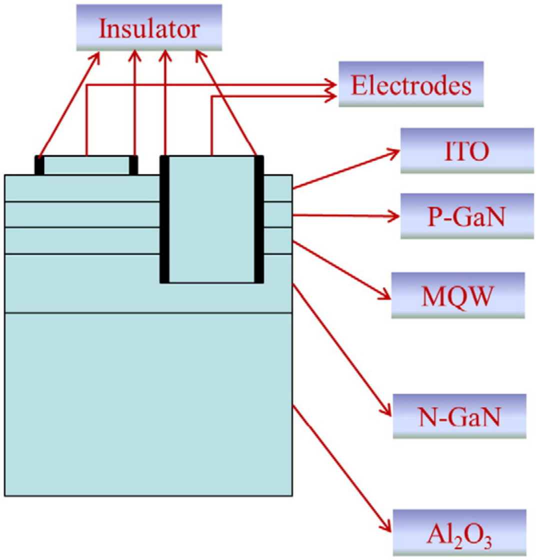

Fig. 1. Illustration of the chip structure.

light efficacy of the LED. However, the reason of the shadowing effect was not explicitly explained in their work.

In this paper, we developed an electro-optical numerical simulation to draw a direct relation between the electrode pattern and the LED light intensity. Effects of the electrode pattern on both the current density distribution on the MQW layer and the light emission out of the LED chip were taken into account in the proposed simulation method. The remaining of the paper is organized as follows: Section II describes the detailed information of the LED chip used in our study. Then the simulation process, results and discussions are presented in Section III and Section IV respectively. Finally, concluding remarks are made in Section V.

2. Sample preparation

The LED chip used in this study was fabricated in-house by growing GaN based epitaxial layers on the c-plane sapphire substrate using the Metal Organic Chemical Vapor Deposition (MOCVD) technique. As illustrated in the Fig. 1, the chip consists of multiple layers including a 120 nm ITO layer, 240 nm Mg doped p-GaN layer, 180 nm InGaN MQW and 2um *Si*-doped n-GaN layer and 150um sapphire substrate from top to bottom. In addition, a surface roughening treatment was performed on the ITO layer to enhance the LEE of the LED chip. And the Ni/Au contact electrodes were fabricated in a typical symmetric shape with 10 um width, surrounded by another 10 um wide SiO_2 insulator layer. Afterward, the chips were diced from the wafer with the size of 45 mil by 45 mil. Fig. 2 shows a close-up shot of the electrode geometry of the prepared chip.

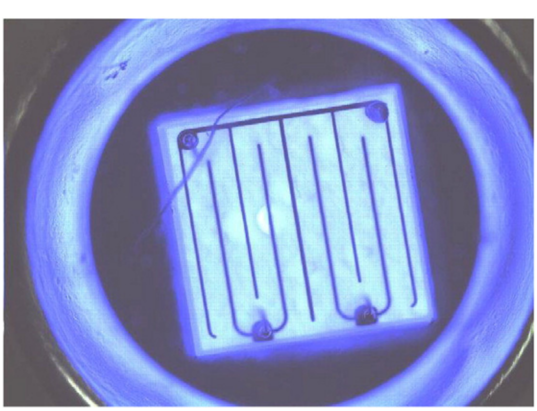

Fig. 2. Photo of the electrode geometry

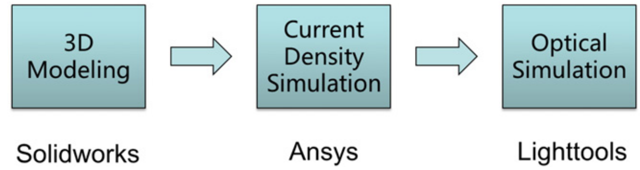

Fig. 3. Illustration of the modeling process of the electro-optical simulation.

3. Simulations

Fig. 3 illustrates the numerical modeling process proposed in this study, which contains three stages. Firstly, a 3D chip model representing the blue chip fabricated in the preceding section was created by the Solidworks. Fig. 4 shows the profile of the model in which the round corners of its electrodes and bonding pads were simplified as rectangular shapes. This can greatly reduce the meshing complexity of the finite element models for electrical simulations, without significantly losing the model accuracy.

Then the established chip model was imported into the ANSYS Multiphysics software to simulate the current density distribution on the MQW layer of the LED chip. The model was meshed using the Solid226 elements. Since the purpose of this simulation is only to calculate the current density distribution on the MQW layer, all materials in the finite element model, including those in the MQW layer, were assumed following the Ohm's Law with simplification. Table 1 gives the properties of materials in different layers of the model, such as the electrical resistivity and thermal conductivity. By applying a 350 mA driving current on the anode of the model and ground potential on the cathode, the current density distribution on the MQW layer was obtained from the simulation.

After the electrical simulation, an optical simulation on the same chip model was further performed using the Lighttools software. As illustrated in the Fig. 5, the chip model was placed on a large substrate. In the optical simulation, the light rays were set to be emitted on the top surface of the MQW layer of the LED chip. Eq. (1) gives the

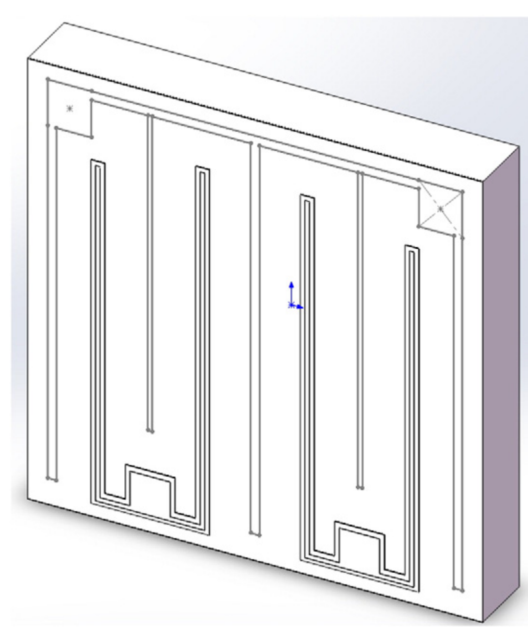

Fig. 4. Profile of the 3D chip model of the blue chip.

Table 1
Summary of material properties in the electrical simulation.

Material	Electrical resistivity [Ω·m]	Thermal conductivity [$W·m^{-1}·K^{-1}$]
Al_2O_3	1.0E1	2.5E1
N-GaN	1.0E-4	2.3E2
MQW	1.5E2	2.3E2
P-GaN	4.2E-2	2.3E2
ITO	5.4E2	7.5E-1
Ni/Au (electrodes)	2.4E-8	2.0E2
SiO_2	1.0E6	7.6E0

theoretical relationship between the distributions of the current density and light emission energy on the MQW layer [8].

$$R(x) = \frac{\gamma \eta_{IQE}}{q} J(x) \tag{1}$$

in which $R(x)$ is light emission energy distribution, $J(x)$ is the current density distribution, γ is the average photon emitted energy from the active layer, η_{IQE} is the internal quantum efficiency and q is the electric charge.

By assuming that the blue chip exhibits a unity η_{IQE} in this paper, a proportional relationship between the current density distribution and light emission energy distribution on the MQW layer was addressed. Thus, in the optical simulation, the light emission on the top surface of the MQW layer was applied to follow the same distribution of the current density distribution extracted from the electronical simulation. To apply this distribution, we equally discretized the MQW layer of the chip model into a 20×20 grid shown in the Fig. 6. The distributed emission light energy was then applied on the top surface of the MQW layer using the spatial apodization based on the averaged current densities of the grid elements. Moreover, a 50% diffusion and a 50% near specular reflection were set on the top surface of the ITO layer to simulate the ITO scattering feature, and a 90% reflectance was set on the top surface of the substrate to simulate the effect of the substrate reflection. In the end, a sphere receiver was built to collect the light energy emitted out of the chip model.

In the optical simulation, the optical properties of each layer in the chip model are given in the Table 2. A number of 500,000 light rays were set to be emitted from the top surface of the MQW layer, and the radiant power out of the chip model was collected by the sphere receiver.

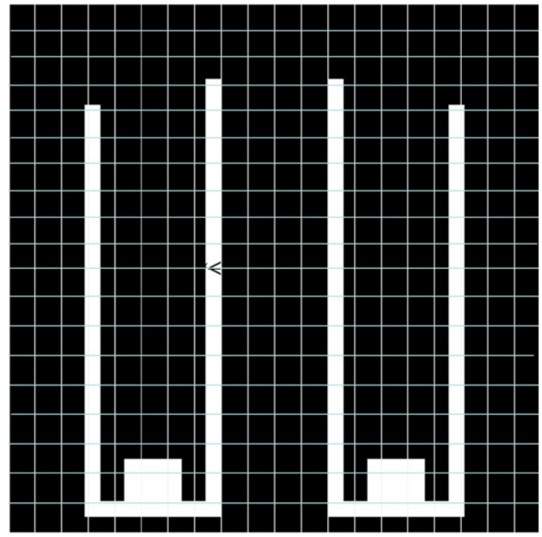

Fig. 6. Discretization of the MQW layer of the chip model.

4. Results and discussions

The vector plot of the current density on the MQW layer is displayed in the Fig. 7. It can be seen that the current flows through the MQW layer along the axial direction of the chip. The current density on the MQW is extremely uneven from 0 to 1.45E6 A/mm^2. As shown in the Fig. 8, a quite high current density is observed in the region below the anode, but it dramatically drops in neighboring areas. This is probably because the ITO layer is not thick enough for getting a good current spreading performance.

From the electrical simulation results, the current density on each grid element of the MQW layer was calculated by averaging the current densities at all nodes within that element. These calculated current densities were further used to distribute the light emission energy on the top surface of the MQW layer. Using the Monte-Carlo ray-tracing simulation, light intensity distribution patterns with respect to the directions from 0° to 175° with an increment of 5° were calculated and recorded. Fig. 9 shows the predicted 0°and 90° angular light intensity distribution patterns. Due to the structural asymmetry between the anode and cathode patterns, the two predicted light intensity distribution patterns are slightly different.

To validate the electro-optical simulation results, the used LED blue chip was bonded in a 5050 LED lead frame and its light intensity

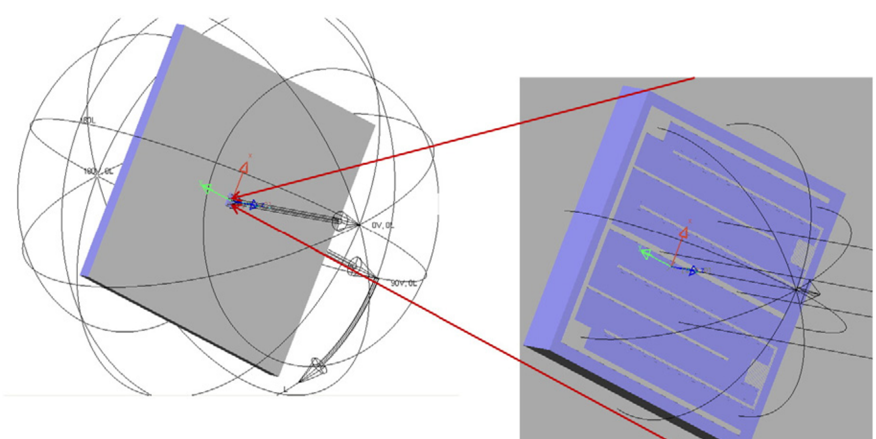

Fig. 5. Illustration of the optical model.

Table 2
Summary of optical properties of each layer in the optical simulation.

Material	Refractive index	Reflectivity	Optical density
Al_2O_3	1.8	/	0.046
N-GaN	2.4	/	0.046
MQW	2.4	/	0.046
P-GaN	2.4	/	0.046
ITO	1.9	/	0.046
Ni/Au (electrodes)	/	1.5	3
SiO_2	1.5	/	0.046

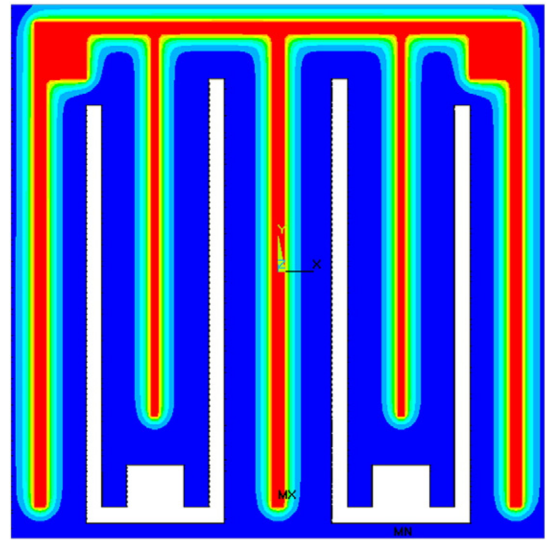

Fig. 8. Contour plot of the simulated current density distribution on the MWQ layer.

distribution pattern was experimentally measured by using a SIG-400 goniometric system. In general, as shown in the Fig. 10, a good agreement is achieved between the simulated and experimental measured light emission distribution patterns, both of which were calculated from the averaged angular light intensity distribution pattern over all directions. Because the inner surface of the lead frame absorbs a small amount of light emitted from the LED chip in the experiment, the experimental measured light intensity is found slightly smaller than the predicted data at low angles closed to the substrate surface.

Next, we investigated the influence of the current density distribution of the MQW layer on LED light intensity to confirm the statement that uniform current density is helpful to improve the LEE of the LED chip [15]. In reality, the performance of such studies usually needs to be characterized with a large amount of experimental works on preparing and testing the LED chip samples. In our study, these efforts can be greatly reduced with the assistance of optical simulations. Similar to the LED chip fabricated in this study, we firstly assumed an ideal LED chip in which an even light emission energy distribution is applied on the top surface of the MQW layer whereas the electrode geometry is not changed. Then, an optical simulation on the ideal LED chip was run to calculate its light intensity distribution pattern. Fig. 11 shows the discrepancy in the light intensity distribution patterns of the LED chips with the unevenly and evenly light emission energy on the MQW layer. The simulation results show that a uniform distribution of the energy emission on the MQW layer enhances the magnitude of the LED light intensity, but does not change the shape of the light intensity distribution pattern. In another word, the optimization of the current density distribution on the MQW layer does not affect the pattern of LED light intensity distribution essentially.

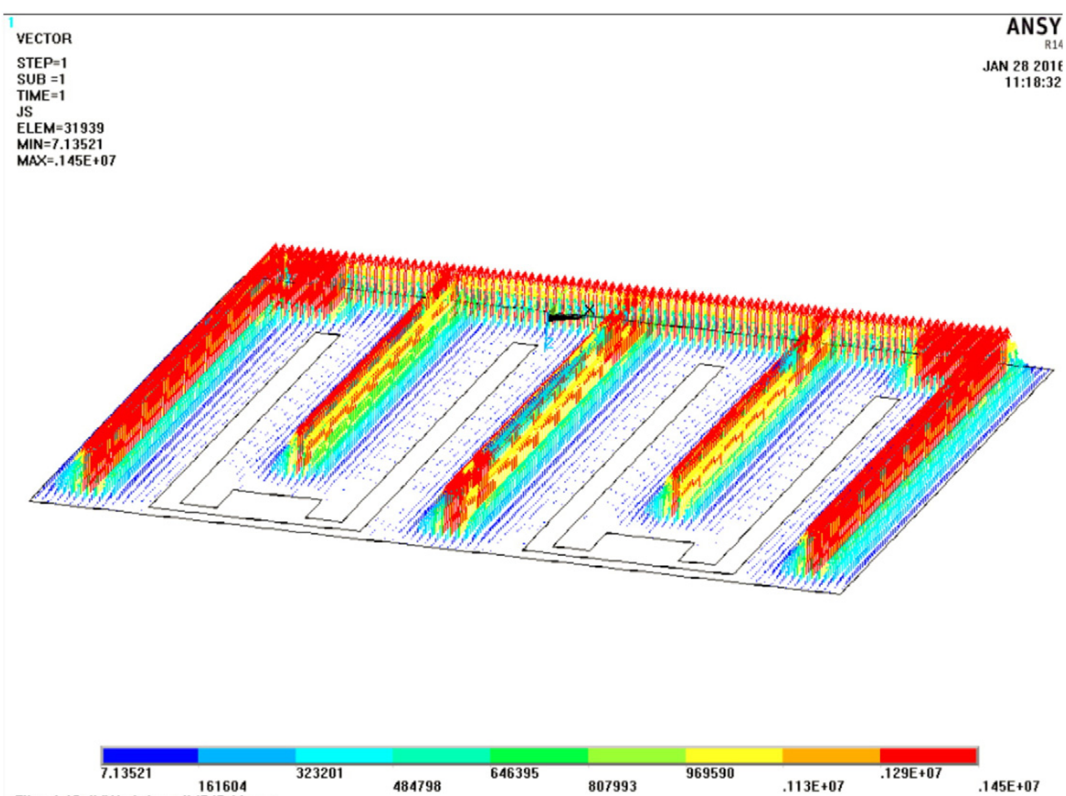

Fig. 7. Vector plot of the density of current flowing through the MQW layer.

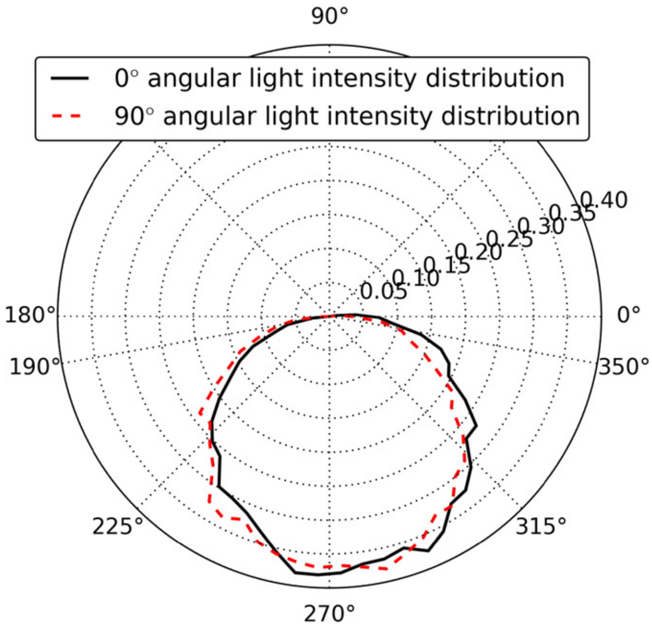

Fig. 9. Predicted 0° and 90° angular light intensity distribution patterns of the LED chip.

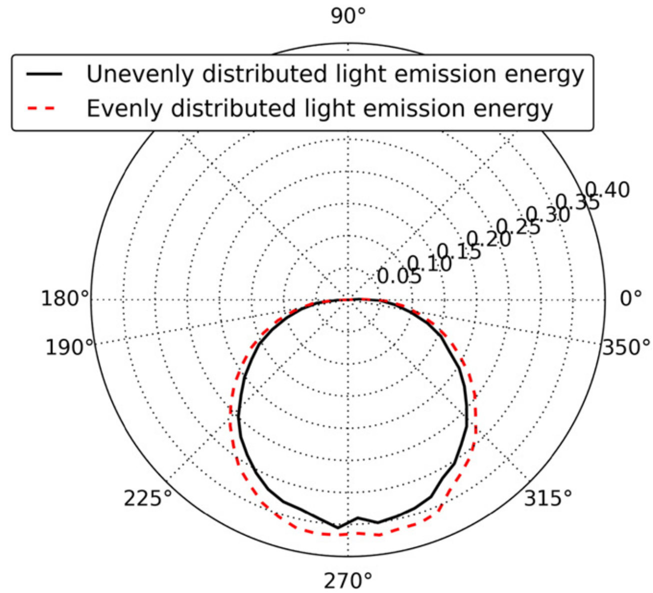

Fig. 11. Comparison of the simulated light intensity distribution patterns by uneven and even distributed light emission energy on the MQW layer.

By using Eq. (2), the luminous fluxes of the test sample with the different light intensity distribution curves shown in the Figs. 10 and 11 can be calculated for a quantitative comparison.

$$\Phi = \int_0^{\pi} I_\theta \times 2\pi \times \sin(\theta) d\theta \quad (2)$$

in which Φ is the luminous flux, I_θ is the light intensity at the horizontal angle θ. These calculated luminous flux results are given in the Table 3. It can be seen that the predicted luminous flux calculated from the light intensity distribution pattern predicted by the electro-optical simulation is 2.13 lm, which is about 6% higher than the experimental value (2.01 lm). Moreover, as also given by the Table 3, the luminous flux calculated from the light intensity distribution pattern predicted by the adapted simulation where the emission energy is assumed evenly distributed on the MQW layer is 2.30 lm, which is 8% higher than the scenario that the emission energy distribution equals to the current density distribution on the MQW layer. This implies the luminous efficacy of the test sample is possible to be further enhanced (up to 8%) by improving the uniformity of the current density distribution on the MQW layer even through the electrode typology while the chip structure is not changed.

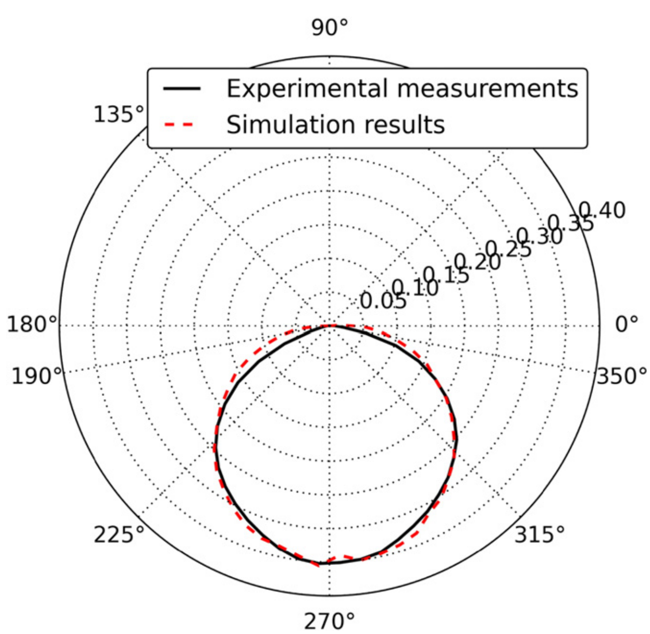

Fig. 10. Experimental and predicted light intensity distribution patterns of the LED chip.

5. Concluding remarks

In this paper, an electro-optical numerical simulation method is proposed to predict the light intensity distribution pattern and luminous flux of an in-house fabricated 4545 blue LED chip. In this method, the electrical and optical simulations of the LED chip model are linked by assuming that the current density and light emission energy on the MQW layer are linearly related. The experimental validation results show that the proposed method can give accurate predictions on both the LED light intensity distribution and luminous flux. According to our simulation results it is theoretically shown that an increase of at most 8% of the luminous flux can be achieved when the current density is managed as evenly distributed on the MQW layer whereas the chip structure and electro pattern remains the same.

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Table 3
Luminous fluxes of the test sample calculated from the light intensity distribution curves in Fig. 10 and Fig. 11.

	Φ (lm)	Calculated from
Experimental	2.01	The black solid curve in Fig. 10
Electro-optical simulation	2.13	The red dashed curve in Fig. 10
Adapted simulation	2.30	The red dashed curve in Fig. 11

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